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Vehicle Dynamics Monitoring and Tracking System (VDMTS): Monitoring Mission Impacts In Support Of Installation Land Management

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ACRONYMS AND ABBREVIATIONS

2DRMS	twice distance root mean square
AAV	Amphibious Assault Vehicle
AFB	Air Force Base
APC	Armored Personnel Carrier
ARC	Army Reconnaissance Course
ARRM	Army Range Requirements Model
ATTACC	Army Training and Testing Area Carrying Capacity
BFT	Blue Force Tracking
BRAC	Base Realignment and Closure
CEP	circular error probable
CERL	Construction Engineering Research Laboratory
cm	centimeter
COTS	commercial off-the-shelf
CWA	Clean Water Act
Cybernet	Cybernet Systems Corporation
DEM	Digital Elevation Model
DFIRST	Deployable Force-on-Force Instrumented Range System
DGPS	Differential Global Positioning System
DoD	U.S. Department of Defense
DPW	Directorate of Public Works
DW	disturbed width
ERDC	Engineer Research and Development Center
ESA	Endangered Species Act
ESTCP	Environmental Security Technology Certification Program
GPS	Global Positioning System
ha	hectare(s)
HDOP	Horizontal Dilution of Precision
HEMTT	heavy expanded mobility tactical truck
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HQDA	Headquarters, Department of the Army
ID	identification
INS	Inertial Navigation System
IS	impact severity (vegetation cover loss)
ITAM	Integrated Training Area Management
LAV	Light Armored Vehicle
LRAM	Land Repair and Maintenance

LMTV	Light Medium Tactical Vehicle
MEMS	micro electro mechanical systems
MODIS	Moderate Resolution Imaging Spectroradiometer
m/s	meters per second
MTV	Medium Tactical Vehicle
NEPA	National Environmental Policy Act
OPAL	Optimal Allocation of Land for Training and Non-Training Uses
POI	Program of Instruction
PTA	Pohakuloa Training Area
QA/QC	quality assurance/quality control
RCW	Red-cockaded Woodpecker
RD	rut depth
RFMSS	Range Facility Management Support System
RTLA	Range and Training Land Assessment Program
SAT	Satellite
SERDP	Strategic Environmental Research and Development Program
TARDEC	Tank Automotive Research, Development, and Engineering Center
TES	threatened and endangered species
TIF	Training Impact Factor
TR	turning radius
USFWS	U.S. Fish and Wildlife Service
UTC	Universal Time Coordinated
UTM	Universal Transverse Mercator
VDMTS	Vehicle Dynamics Monitoring and Tracking System
VDM	Vehicle Dynamics Monitor
VTI	Vehicle Terrain Interface
VTS	Vehicle Tracking System
WAAS	Wide Area Augmentation System

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1.0 EXECUTIVE SUMMARY

1.1 OBJECTIVES OF THE DEMONSTRATION

The use of military vehicles during training results in soil disturbance and vegetation loss, with subsequent increases in soil erosion rates, sedimentation in streams, habitat degradation, and numerous other secondary effects. The National Environmental Policy Act (NEPA) requires federal agencies to evaluate the implications of their plans, policies, programs, and projects. However, accurate assessment of military training impacts is limited by the technical data available to support the assessments. This project demonstrated the use of the Vehicle Dynamics Monitoring and Tracking System (VDMTS) to assess and predict military vehicle maneuver training impacts for use in land management decision making and NEPA documentation. The objective of this project was to demonstrate and validate the VDMTS system and its components through a series of controlled field studies and live tracking events. A controlled field study was used to demonstrate and validate that the hardware can sufficiently characterize vehicle dynamic properties (turning radius and velocity) to accurately predict site impacts (area impacted, vegetation loss, and rut depth [RD]). A controlled field study was used to demonstrate and validate the accuracy of VDMTS impact models in predicting area impacted, vegetation loss, and RD for a range of vehicles. Field studies tracking live training exercises and subsequent field measurements were used to demonstrate and validate the VDMTS hardware and model performance in predicting site impacts.

1.2 TECHNOLOGY DESCRIPTION

The VDMTS approach is composed of three components: 1) vehicle impact models, 2) vehicle tracking hardware and software, and 3) vehicle tracking data analysis. The approach spatially characterizes short-term, direct impacts by monitoring individual vehicle locations and operating characteristics. These dynamic characteristics are used to predict area impacted, vegetation loss, and RD based on vehicle type and location. Results are summarized to characterize training land use patterns and quantify the severity of the training impacts.

The process-based impact models predict terrain impacts caused by wheeled and tracked vehicles in terms of percent vegetation cover loss (impact severity [IS]), disturbed width (DW), and RD. Impact models predict site impacts based on vehicle static (i.e., vehicle weight and type), vehicle dynamic properties, and soil properties (soil strength). The process uses vehicle tracking systems to determine vehicle location and dynamic operating characteristics (i.e., turning radius and velocity). The VDMTS hardware consists of a Global Positioning System (GPS) receiver integrated with low-cost inertial sensors. These sensors enable measurement of vehicle kinematics, dynamics and other parameters of interest that enable accurate modeling of environmental impact. The system thereby provides vehicle dynamics data and positional information at all times, even when GPS is unavailable.

The vehicle tracking data are analyzed and summarized into formats appropriate for land management decisions. Analysis routines include: 1) identification of individual and unit tracking patterns, 2) identification of on- and off-road use patterns, 3) identification of existing and emerging trail networks, 4) vegetation loss estimates, 5) identification and prioritization of Land Repair and Maintenance (LRAM) sites, and 6) development of data for carrying capacity models.

1.3 DEMONSTRATION RESULTS

This demonstration/validation project tested and validated each aspect of the VDTMS process at multiple levels, specifically, accuracy of the hardware and models in combination, durability of the hardware under multiple training events, ease of use of the VDTMS process, and ability to make land-use decisions based on the VDMTS collected and summarized data. The following quantitative metrics were tested to assess each aspect of VDMTS performance: 1) accurate VDMTS hardware measurement of vehicle dynamic properties, 2) accurate VDMTS impact model predictions of site impacts under controlled conditions, 3) accurate VDMTS hardware measurement of vehicle static and dynamic properties, 4) accurate VDMTS model predictions of site impacts during live training, 5) VDMTS hardware durability (in single live training event), 6) VDMTS hardware durability over 14 live training events, 7) ease of system use, and 8) quality and accuracy of data for land-use decisions.

Of the hardware performance metrics cited in the above paragraph, 1, 3, and 5-8 were met. Metrics 2 and 4, accurate VDTMS impact model predictions in controlled and live events, did not meet the success criteria initially proposed. The demonstrated average error for DW was 14.9 centimeters (cm), and the average error for vegetation removal was -1.8%. These results are comparable with existing site and vehicle-specific empirical model predictions, thus reducing the need to develop models for each site. This validates the use of the theoretical models for impact prediction.

The system met most of the metrics established. While it failed to meet some metrics, it still performed as well as previous methods in characterizing vehicle impacts, reducing the relative cost and time required. Project success was indicated by the use of data obtained from the system by the installation hosts as well as their quick implementation of the technology. Through the course of the project, installation Integrated Training Area Management (ITAM), Environmental, Directorate of Public Works (DPW), and training groups have used results obtained from this study. Data collected were used in land management and vehicle mobility and power models. Study results also informed training and regulating decisions.

1.4 IMPLEMENTATION ISSUES

Implementation of the VDMTS approach will generally be driven by installation land manager requirements. Despite installation acceptance of the process, the main implementation issue may be caused by turnover in the ITAM and Environmental installation branches. A lack of continuity in programs from this turnover may result in issues incorporating the system into that program. An additional option for implementation involves using existing military standard systems (the Army's Blue Force Tracking [BFT] and the National Guard's Deployable Force-on-Force Instrumented Range System [DFIRST]), which obtain vehicle location and time data on live training events for post-event analysis. This option would decrease costs by reducing the time and equipment required to obtain vehicle tracking data. However, this process is still being developed and is not available widely at this time. The VDMTS technology has been and will continue to be valuable in obtaining data to estimate impacts from military training. This Cost and Performance Report assists installations in making informed decisions regarding technology implementation and associated costs.

2.0 INTRODUCTION

2.1 BACKGROUND

The use of military vehicles during training results in soil disturbance and vegetation loss, with subsequent increases in soil erosion rates, sedimentation in streams, habitat degradation, and numerous other secondary effects. The capacity of installation lands to support training activities is a function of the sensitivity of lands to specific activities, the natural recovery rates of vegetation, the weapon system characteristics, the doctrine that establishes how these systems are used, and the actual locations where activities are conducted. Accurate assessment of these impacts is limited by the technical data available to support the assessments. The VDMTS consists of three components: 1) vehicle impact models, 2) vehicle tracking hardware and software, and 3) vehicle tracking data analysis. The vehicle impact models are theoretical, process-based vehicle impact models used to predict site impacts in terms of disturbed area, vegetation loss, and RD. Data collected by the VDMTS hardware are used with the impact models to predict spatially explicit site impacts. After a decision to field weapon systems is made at an installation, vehicle tracking systems provide both a new capability and a proactive means for the installation to monitor land condition and preemptively implement LRAM programs. The direct monitoring of mission impacts allows land managers to locate the most severe impacts after training events and mitigate initial site damage before lands further degrade.

2.2 OBJECTIVE OF THE DEMONSTRATION

The objective of this project was to demonstrate and validate the VDMTS system and its components through a series of controlled field studies and live tracking events. A controlled field study was used to demonstrate and validate that the hardware can sufficiently characterize vehicle dynamic properties (turning radius and velocity) to accurately predict site impacts (area impacted, vegetation loss, and RD). A controlled field study was used to demonstrate and validate the accuracy of VDMTS impact models in predicting area impacted, vegetation loss, and RD for a range of vehicles. Field studies tracking live training exercises and subsequent field measurements were used to demonstrate and validate the VDMTS hardware and model performance in predicting site impacts.

2.3 REGULATORY DRIVERS

NEPA requires federal agencies to evaluate the environmental implications of their plans, policies, programs, and projects, at the same time traditional economic and technical evaluations are underway. The Federal Water Pollution Control Act, commonly referred to as the Clean Water Act (CWA), is intended to restore and maintain the chemical, physical, and biological integrity of the nation’s waters by preventing point and nonpoint pollution sources. Off-road vehicle-based maneuver training is a major contributor to accelerated erosion on military lands and can be in violation of the CWA. Section 7 of the Endangered Species Act (ESA) requires federal agencies to ensure that the actions they take, including those they fund or authorize, do not jeopardize the existence of any listed species. If a federal agency action is important (i.e., live training), the motivation is for the federal landowner to provide data to support their position.

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3.0 TECHNOLOGY/METHODOLOGY DESCRIPTION

This section describes the VDMTS vehicle-based maneuver impact assessment process. A description of the technology and theoretical models utilized in the system is given. This section also summarizes the advantages and disadvantages of utilizing the VDTMS process as opposed to alternative technologies.

3.1 TECHNOLOGY/METHODOLOGY OVERVIEW

The VDMTS approach is used to assess and predict impacts resulting from military vehicle-based maneuver training. The approach consists of vehicle impact models, vehicle tracking hardware and software, and vehicle tracking data analysis. Each component of the VDMTS approach is discussed in more detail in the following subsections.

3.1.1 Vehicle Tracking Processes

The VDMTS process is illustrated in Figure 1. The process uses vehicle tracking systems to determine vehicle location and dynamic operating characteristics (i.e., turning radius and velocity). The VDMTS vehicle hardware is GPS-based with inertial sensors (Cybernet, 2002; 2004). This component of the VDMTS system is shown in the activity characterization step of Figure 1. Alternative methods such as custom-built vehicle tracking systems with commercial off-the-shelf components and military standard training systems (Army's BFT and National Guard's DFIRST) could also be used to collect the vehicle dynamic operating characteristics (Anderson et al., 2009; Svendsen et al., 2011).

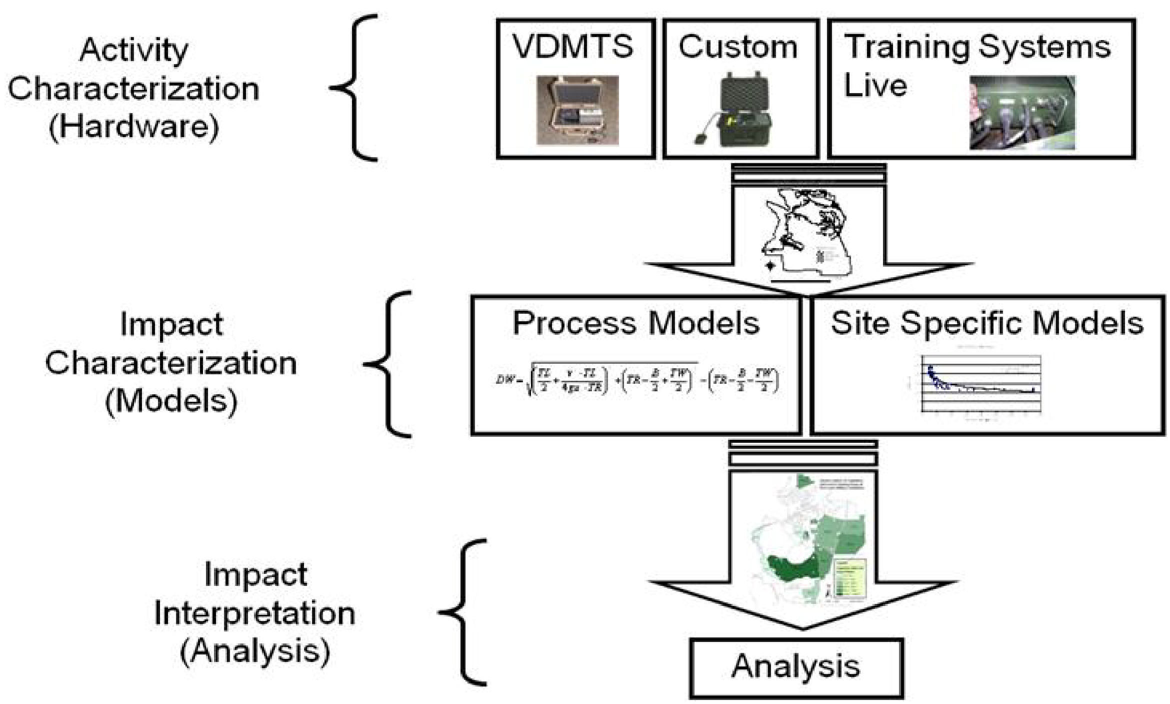

Figure 1. Vehicle tracking and impact analysis approach.

Process-based vehicle impact models were developed through a series of controlled replicated studies (Ayers et al., 2005; Ayers et al., 2006; Foster et al., 2006; Haugen et al., 2003). Impact models were developed from the field data (Li et al., 2007a; Li et al., 2007b). The process-based impact models are indicated in the Impact Characterization step in Figure 1. An alternative method of determining impacts is to implement the system used prior to the development of the theoretical models: performing field impact assessments and developing site-specific regression models. VDTMS data analysis routines are used to post-process tracking data. Analysis routines include spatial displays of estimated vegetation loss and soil rutting, percent of vegetation lost within management areas, percent on- and off-road traffic, potential trail identification (Anderson et al., 2007a,b; Ayers et al., 2005; Haugen et al., 2003; Rice et al., 2006; Wu et al., 2004; Wu et al., 2006; Wu et al., 2007).

3.1.2 Vehicle Impact Models

The process-based impact models predict terrain impacts caused by wheeled and tracked vehicles in terms of percent vegetation cover loss (IS), DW, and RD. Percent vegetation loss is the primary measure of site impact because it is a primary variable used in Army operational monitoring programs and an input variable to many ecological models. DW is required to convert linear distance traveled to an area impacted. RD is estimated because this variable is highly correlated with vegetation recovery rates and is important to models that incorporate microtopography. Individual models were developed for tracked vehicles and for four-, six-, and eight-wheeled vehicles. Equation 1 shows the DW model for tracked vehicles. The full derivation of the tracked model can be found in Li et al. (2007b). A similar process-based, theoretical model was developed for DW from wheel vehicles. DW equations and their derivation for wheeled vehicles are documented in Li et al. (2007a).

$$DW = \sqrt{\left(\frac{TL}{2} + \frac{v^2 \cdot TL}{4g\mu_1 \cdot TR}\right)^2 + \left(TR - \frac{B}{2} + \frac{TW}{2}\right)^2} - \left(TR - \frac{B}{2} - \frac{TW}{2}\right) \tag{1}$$

Process-based theoretical models were developed to estimate percent vegetation loss based on vehicle type, vehicle dynamic properties, and vehicle static properties. Individual models were developed for tracked vehicles and for four-, six- and eight-wheeled vehicles. Equation 2 shows the vegetation loss model for tracked vehicles. The full derivation of the tracked model can be found in Li et al. (2007b). Higher shear stresses produced at the terrain surface result in more shear displacement and, consequently, greater vegetation loss. The vegetation cover and the surface soil are completely scraped away when the shear stress reaches the maximum strength that the soil can sustain.

$$IS = \left(1 - e^{-j/K - 0.233}\right) \times 100\% \tag{2}$$

Where:

- IS = vegetation loss (impact severity), [%]
- j = shear displacement, [m]
- K = the shear deformation modulus, [m]
- e = approximately 2.718

Vegetation loss equations and their derivation for wheeled vehicles are documented in Li et al. (2007a). A critical velocity, v_{cri}, is derived by balancing soil friction forces with centrifugal

forces. The critical velocity is defined as the vehicle speed where soil shear stress is equal to the soil shear strength. The vegetation loss is calculated from a ratio of actual vehicle velocity to the critical velocity. Any increase in velocity beyond the critical velocity results in the vehicle sliding laterally and complete vegetation removal.

These models are predictive in two respects. First, vegetation loss is not measured in the field but predict based on vehicle characteristics (static and dynamic) and site conditions (soil strength). Second, predictions can be made for other site conditions (i.e., wetter or dryer conditions). Using the same live event tracking data, predictions can be made for vegetation loss in wet soils, even if the event may have occurred during dry conditions. This prediction assumes that wet conditions do not change the pattern of vehicle training, only the magnitude of vegetation loss.

RD or sinkage models have been developed by the U.S. Army Engineer Research and Development Center (ERDC). The Vehicle Terrain Interface (VTI) is a vehicle terrain interaction model that predicts sinkage for vehicles in different soil conditions (Richmond et al., 2004: Jones et al., 2007; Nunez et al., 2004). However, vehicle-operating characteristics (turning radius [TR] and velocity) are not inputs in this model. Liu et al. (2010) modified the VTI model to incorporate weight shift due to changes in TR and velocity.

3.1.3 Vehicle Tracking Hardware and Software

A low-cost VDMTS was developed to automate and enhance the process of understanding the spatial and temporal characteristics of vehicle-based impacts for assessing land condition, estimating land capacity, and restoring lands in support of DoD training requirements (Figure 2). The VDMTS hardware consists of a GPS receiver integrated with low-cost micro electro mechanical systems (MEMS)-based strap down inertial sensors. These sensors enable measurement of vehicle kinematics, dynamics, and other parameters of interest that enable accurate modeling of environmental impact. The system thereby provides vehicle dynamics data and positional information at all times, even when GPS is unavailable. The VDMTS has the capability to record the vehicle dynamics tagged with position information for accurate and enhanced post-mission analysis at substantially reduced costs. Onboard system data storage provides archival data for post-training event analysis.

Figure 2. VDMTS hardware.

The photo on the left illustrates the hardware in the durable case. The photos on the right illustrate the front and back panels of the VDMTS unit.

3.1.4 Vehicle Tracking Data Analysis Routines

Analysis routines were developed to help users interpret the vehicle tracking data. The assessment of individual vehicle impacts and impact patterns is intended to address management issues like the ones listed below:

1. How much damage does one type of vehicle cause relative to other vehicles?
2. How much damage does a group of vehicles conducting a training exercise cause relative to other training events?
3. Do the spatial impact patterns for individual units and events differ from the historic patterns? Should we expect new areas to be impacted that have not historically been impacted?
4. How much time do vehicles spend in areas designed to minimize vehicle impacts? How much time is spent in critical habitat or near critical resources like cavity trees?
5. Where can we expect new trail networks to form?

Methods were developed to identify areas with single and multiple tracking within an event (Wu et al., 2004; Rice et al., 2006). Tabular summaries identify important model input data for other environmental models (Anderson et al., 2007a and b). Another example is percent off-road travel and average vegetation cover loss per mile for development of Army Training and Testing Area Carrying Capacity (ATTACC) Training Impact Factor (TIF) parameter development (Anderson et al., 2007a).

3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY/ METHODOLOGY

The VDMTS approach gives installation land managers a tool to quantitatively assess impacts resulting from training activities. The predictive models also allow assessment of training impacts given future training missions and weapon systems. Several current DoD technologies exist that at least partially meet the need addressed by the VDTMS. The VDTMS approach is limited by the requirement to track training events to collect required data. This limitation could be relieved by utilizing DoD standard training and tracking systems (e.g., DFIRST, BFT) to obtain required dynamic vehicle use data.

The Army Range Requirements Model (ARRM) is a planning tool that models training throughput requirements for all Army installations. It allows for calculations of predicted training miles by unit and event. However, the training data are only at the installation level and do not allow for site impact predictions. The Range Facility Management Support System (RFMSS) tool is a range and training area scheduling tool. It allows for quantification of training at the training area level; however, it is difficult to quantify site impacts from this data. The Range and Training Land Assessment (RTLA) program monitors training land condition and land use intensity. It can provide temporally and spatially explicit patterns of training impacts when combined with ARRM or RFMSS data. Data are available only on annual time intervals and is not component (training event/unit) defined and does not allow for estimation of future impacts given a change in doctrine or weapon system. Installation Specific Vehicle Impact

Studies have been performed for NEPA documentation. These studies are very expensive and it is often difficult to extrapolate data to actual unit/event impacts.

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4.0 PERFORMANCE OBJECTIVES

Performance objectives are provided in Table 1. Performance metrics included qualitative and quantitative parameters. Quantitative parameter threshold values were based on information from prior studies. For example, thresholds for accuracy requirements for predicted DW, vegetation loss, and RD were based on 1) variation typically seen in field measurements of the variable; 2) variation in predicted impacts associated with variations in input parameters; 3) limitation introduced from other sources of the model, hardware, or computations; 4) attempt to balance data collection costs and data quality; and 5) accuracy required to make management decisions. The metrics are based on data that were collected in the field. Performance metrics are organized by demonstration/validation study component and methodology component.

Table 1. Performance objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives - Demonstration Plan for Controlled Field Study and Live Training Single Event Study				
1. Accurate VDMTS hardware measurement of vehicle dynamic properties	1.1. VDMTS hardware with Inertial Navigation System (INS) provides more accurate dynamic vehicle properties than GPS alone.	• Vehicle position data without GPS signal	• Ability to record in situations when GPS signals not available due to topography, vegetation, and related conditions	• Success criteria met: Hardware with INS improved dynamic property measurement
	1.2. VDMTS hardware provides sufficient dynamic vehicle properties to predict vegetation loss and soil rutting.	• Vehicle positional accuracy • Vehicle turning radius accuracy • Vehicle velocity accuracy	• Vehicle positional accuracy within 5 m (16.4 ft) 95% of the time • Vehicle turning radius within 10 m (32.8 ft) 95% of the time • Vehicle velocity within 2.24 m per second (m/s) (5 mph) 95% of the time	• Success criteria met: Position within 5 m 99.9% of recording time • Average positional accuracy = 2.05 m • Success criteria met: TR within 10 m 95% of the time • Success criteria met: Velocity within 2.24 m/s 100% recording time • Average velocity error = -0.07 m/s
2. Accurate VDMTS impact model predictions of site impacts under controlled condition	2.1. Correspondence between predicted and measured DW, vegetation loss, and RD of site damage associated with individual vehicle use.	• DW • Vegetation loss • RD	• Correlation between predicted and measured DW >0.8 • Predicted DW within 20 cm of actual DW for 95% of sample points • Correlation between predicted and measured vegetation loss >0.7 • Predicted vegetation loss within 20% of actual vegetation loss for 95% of sample points • Correlation between predicted and measured RD >0.6 • Predicted RDs within 3 cm of actual RDs for 95% of sample points	• Success criteria met: Correlation between predicted and measured DW = 0.89 • Success criteria not met: Predicted DW within 20 cm of actual DW for 50% of sample points • Success criteria met: Correlation between predicted and measured vegetation loss >0.9 • Success criteria not met: Predicted vegetation loss within 20% of actual vegetation loss for 86% of sample points • Success criteria not met: Correlation between predicted and measured RD <0.6 • Success criteria not met: Predicted RDs within 3 cm of actual RDs for 94% of sample points

Table 1. Performance objectives (continued).

Performance Objective	Metric	Data Requirements	Success Criteria	Results
3. Accurate VDMTS hardware measurement of vehicle static and dynamic properties	3.1. VDMTS hardware provides sufficient static and dynamic vehicle properties to predict vegetation loss and soil rutting without GPS signal.	• Vehicle positional accuracy	• Vehicle positional accuracy within 10 m (32.8 ft) for 300 m (984.2 ft) after GPS signal lost 90% of time	• Success criteria met: Vehicle positional accuracy within 10 m (32.8 ft) for 300 m (984.2 ft) after GPS signal lost 100% of time. • Average GPS signal error 1.6 m (±0.1 m) • Average error between INS and GPS data 0.164±0.002 m
4. Accurate VDMTS model predictions of site impacts during live training	4.1. Correspondence between predicted and measured DW, vegetation loss, and RD of site damage associated with vehicle use	• DW • Vegetation loss • RD	• Predicted DW within 20 cm of actual DW in 90% of the sample sites • Predicted vegetation loss within 20% of actual vegetation loss in 80% of the sample sites • Predicted RD within 4 cm of actual RD in 80% of the sample sites	• Success criteria not met: Predicted DW within 20 cm of actual DW in 45.6% of the sample sites • Average error between predicted and measured data = 14.9 cm • Success criteria met: Predicted vegetation loss within 20% of actual vegetation loss in 95% of the sample sites • Average error between predicted and measured vegetation loss = -1.8% • Success criteria met: Predicted RD within 4 cm of actual RD in 100% of the sample sites • Average error between predicted and measured RD = 0.1 cm
5. VDMTS hardware durability	5.1. Reliable hardware use	• Percent of recording time captured	• Percent of recording time >80% of military unit training time	• Success criteria met: 85.5% of military training time recorded.

Table 1. Performance objectives (continued).

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives - Demonstration Plan for Live Training Multiple Event Study				
6. VDMTS hardware durability	6.1. Reliable hardware use	• Percent of recording time captured	• Percent of recording time >80% of training time per vehicle type for any event	• Success criteria met: 90.2% of total training time recorded ($p = 0.0002$) • >80% training time by vehicle recorded except for heavy expanded mobility tactical truck (HEMTT)
7. Ease of system use	7.1. Ability of a technician-level individual to install and maintain hardware	• Training time • Hardware setup/take-down time	• <4 hr/person • <1 hr total/vehicle (setup and take-down)	• Success criteria met: 0.3 hr/person ($p<0.05$) • Success criteria met: 0.19 hr/vehicle ($p<0.05$)
	7.2. Ability of a technician-level individual to retrieve and quality assurance/quality control (QA/QC) data	• Training time • QA/QC time	• <4 hr/person • <1 hr/vehicle data file	• Success criteria met: 1.07 hr/person training time ($p<0.05$) • Success criteria met: 0.82 hr/vehicle data file QA/QC time ($p<0.05$)
	7.3. Ability of a technician-level individual to summarize results	• Training time • Analysis time	• <16 hr/person • < 8 hr/event analysis	• Success criteria met: 6.33 hr/person training time ($p<0.05$) • Success criteria met: 5.45 hr/event average analysis time ($p<0.05$)
8. Quality and accuracy of data for land-use decisions	8.1. Ability to use data for parameterization of models	• Vehicle position • DW • Vegetation loss • Time off road	• <10 m position error • <20% error for time off-road, and IS	• Success criteria met: 1.6 m position accuracy • Success criteria met: 6.3% error IS • Success criteria met: 1.0% error estimating time off-road
	8.2. Ability to use data to identify training area use patterns	• Vehicle positional accuracy • Vegetation loss	• <10 m position error for LRAM identification (ID) • <5 m position error for threatened and endangered species (TES) habitat analysis • <20% error in vegetation loss	• Success criteria met: 1.6 m position error for LRAM ID • Success criteria met: 1.6 m position error for TES habitat analysis • Success criteria met: 6.3% error estimating vegetation loss

Table 1. Performance objectives (continued).

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Qualitative Performance Objectives - Demonstration Plan for Live Training Multiple Event Study				
9. Ease of system use	9.1. Ability of a technician-level individual to install, remove, and review collected data	• Questionnaire feedback from the technician on usability of hardware	• Usable hardware system, QA/QC process, and analyses processes	• Success criteria met: Usable hardware system, QA/QC process, and analyses processes
10. Quality and accuracy of data for land-use decisions	10.1. Ability to use data for parameterization and identifying training area use patterns	• Questionnaire feedback from researchers on usability of system results	• Usable analysis results	• Success criteria met: Usable analysis results

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5.0 SITE DESCRIPTION

This section provides a short description of the selected demonstration sites. The two main demonstration sites are Fort Riley, KS, and Fort Benning, GA, with additional studies performed at Eglin Air Force Base (AFB), FL, and Pohakuloa Training Area (PTA), HI. The combination of the four sites provides a broad range of site characteristics (topography, soil, and vegetation), vehicle types, and training doctrine.

5.1 SITE SELECTION

For this study, Fort Riley was considered the alpha test site. Fort Riley data were utilized in original impact model development and concept development. As such, use of impact models at this location provided a test of the models and technology within the model development parameters. Fort Riley also represents a less stressing environment in that it is relatively flat open grasslands with little GPS signal interference. Fort Benning was considered the beta test site. No data from Fort Benning were used in the development of the model. As such, this demonstration site represents an evaluation of the models/technology outside the original bounds of model development. Fort Benning's topography and vegetation are more diverse allowing for a more robust evaluation of the VDMTS' GPS/INS tracking capabilities. Eglin AFB was chosen as an alternative site for Fort Benning for the controlled vehicle impact test. Installation land managers at PTA expressed interest in using the VDMTS system to identify vehicle impacts in the newly opened Keamuku Training Area. This location allowed the system to be tested and validated under different conditions and on different vehicle types.

5.2 SITE LOCATION, HISTORY, AND SITE CHARACTERISTICS

5.2.1 Fort Riley, KS

Fort Riley is located in northeastern Kansas, USA (Figure 3). This installation has an area of 41,154 hectares (ha). It is located in the Bluestem Prairie region and is characterized by rolling plains and dissected by stream valleys. Installation lands are a mix of native prairie and introduced vegetation. Since the early 1940s, a variety of military training activities including field maneuvers, combat vehicle operations, mortar and artillery fire, and small-arms fire have taken place at Fort Riley. Typical maneuvers by large tracked and wheeled vehicles that traverse thousands of hectares in a single training exercise can cause impacts ranging from minor soil compaction and lodging of standing vegetation to severe compaction and complete loss of vegetative cover in areas with concentrated training use. Figure 3 shows the study areas at Fort Riley. The controlled field study site location was selected to have access to installation representative soil and vegetation types without conflicting with ongoing training activities. The live training event study site location identifies the region most commonly used by maneuver training events.

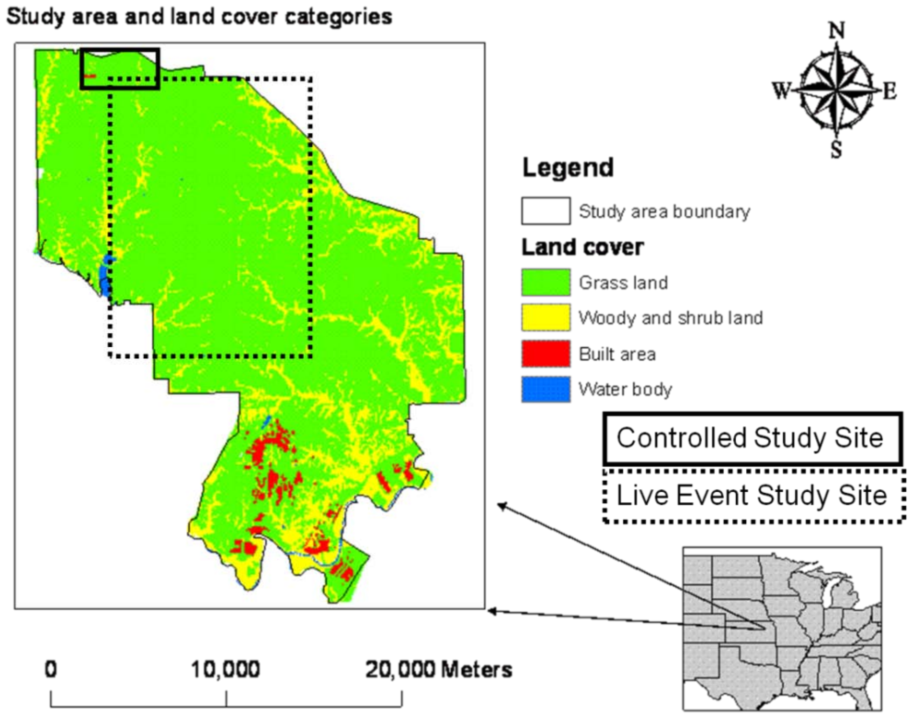

Figure 3. Fort Riley controlled field study and live training event study locations.

5.2.2 Fort Benning, GA

Fort Benning is located in southwest Georgia (Figure 4). The base is 73,503 ha in size. Most of the installation lies in west central Georgia, but a small part extends into Russell County, Alabama. The installation is situated on the Fall Line transition zone, which is the geographic area between the Southern Appalachian Piedmont and the Coastal Plain. Soils are composed of clay beds, weathered Coastal Plain material, and alluvial deposits from the Piedmont (Knowles and Davo, 1997). Open areas are used for military training or managed for wildlife openings. The military open areas are frequently clear-cut parcels of land dominated by grass and bare soil. Since the early 1920s, land impacts due to light and heavy military activities (e.g., infantry, artillery, wheeled, and tracked vehicle training) frequently occur in open areas. Because of Base Realignment and Closure (BRAC), the U.S. Army Armor Center and School is currently being relocated to Fort Benning. Heavy military training will be increased from historical levels, especially in the southern Good Hope Maneuver Training Area. Figure 4 shows the study areas at Fort Benning. The live training event study site location identifies two regions most commonly used by maneuver training events.

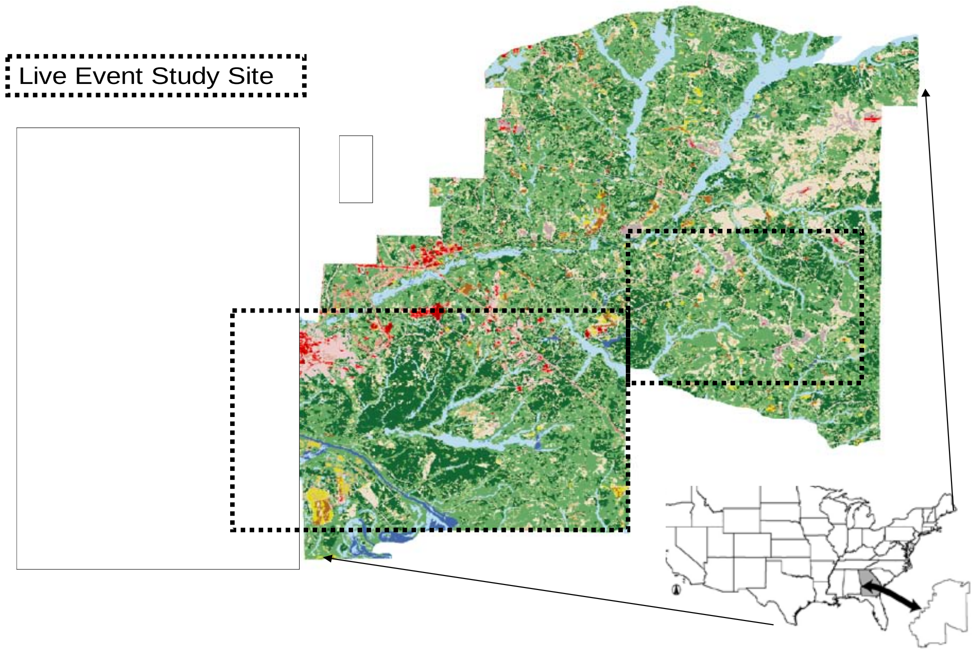

Figure 4. Fort Benning controlled field study and live training study locations.

5.2.3 Eglin Air Force Base, FL

Eglin AFB is located on the Florida panhandle (Figure 5). It is the largest forested military reservation in the United States consisting of 187,995 ha within Santa Rosa, Okaloosa, and Walton counties (U.S. Air Force, 2010). Eglin AFB has a subtropical climate characterized by humid warm summers and mild winters. A majority of the soils on Eglin AFB belong to the Lakeland Association with Lakeland sand the dominate soil type. Eglin's sandhills are comprised of old growth longleaf pine forests with grasses, forbs, and low stature shrub groundcover. This structure is maintained by frequent fires (3-5 year frequency). Eglin AFB is the largest and least fragmented single longleaf pine ownership in the world.

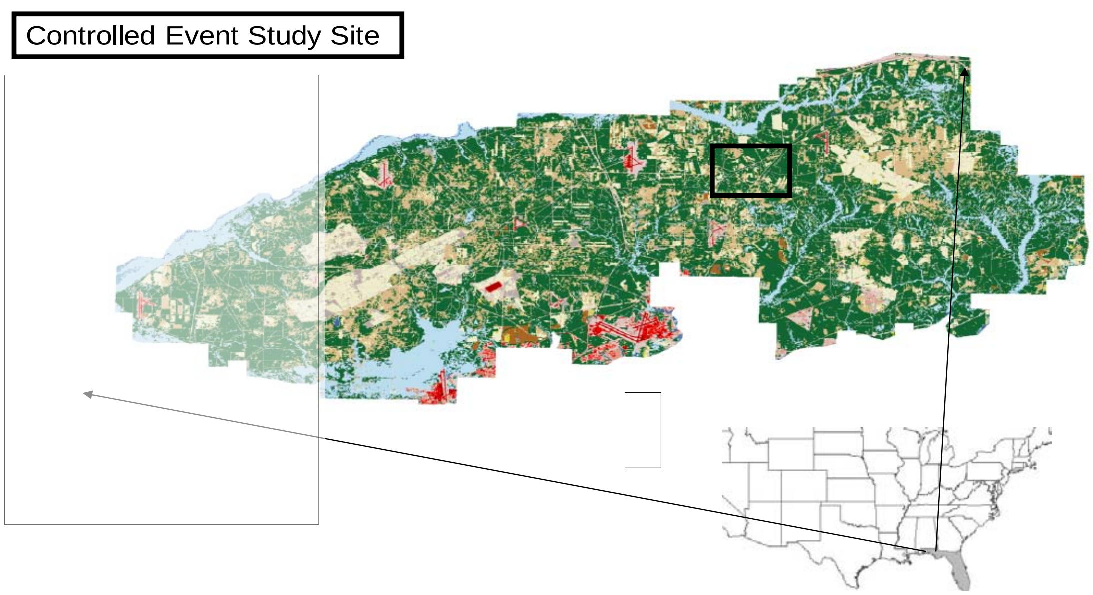

Figure 5. Eglin AFB controlled field study location.

5.2.4 Pohakuloa Training Area, HI

PTA is located on the island of Hawaii (Figure 6). It is 53,735 ha in size making it the largest Army training area in Hawaii (U.S. Army Environmental Command, 2008). The installation is located in the saddle between Mauna Loa and Mauna Kea volcanoes. PTA is located in the Hawaiian Islands Province of the Rainforest Division (Bailey, 1995). Soils on PTA are thin and poorly developed. The predominant soil types are Keekee loamy sand and Kilohana loamy fine sand, formed in volcanic ash, sand, and cinders. Grassland, shrubland, and treeland make up the vegetation communities at PTA. PTA is utilized for maneuver unit live-fire, maneuver training, and artillery live-fire (U.S. Department of the Army, 2002). In 2006, the 9210 ha Keamuku Training Area was added to PTA to support battalion maneuver training and to support training of the Stryker Brigade Combat Teams. Figure 6 illustrates the study areas at PTA. The Controlled Event study site was located in the recently acquired Keamuku Training Area. Training monitored under the Live Event study occurred all throughout PTA, including the Keamuku Training Area.

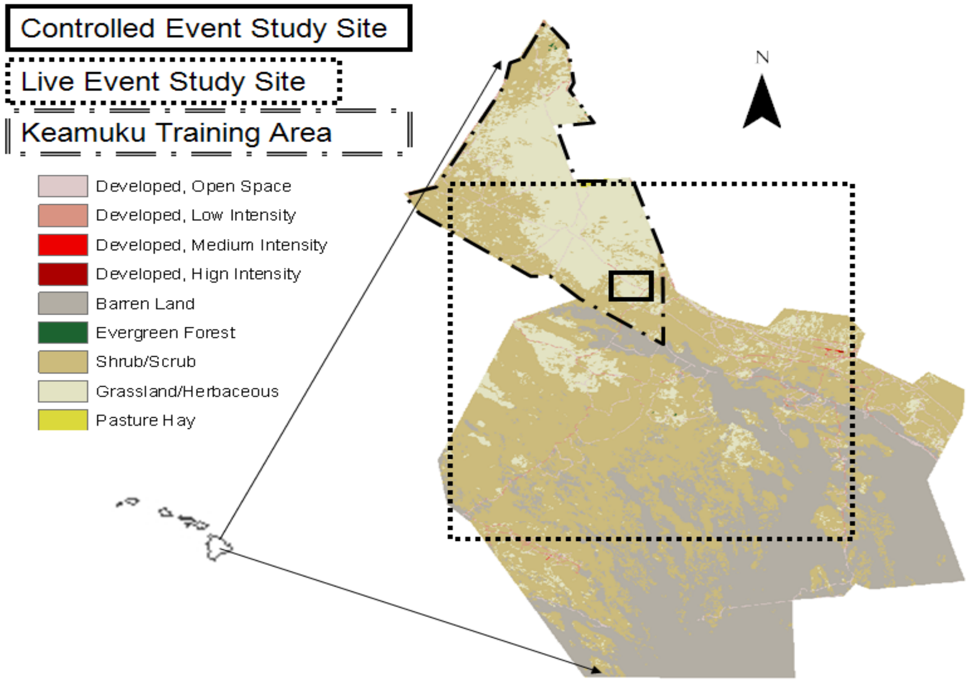

Figure 6. PTA controlled field study and live training event study locations.

6.0 TEST DESIGN

6.1 CONCEPTUAL TEST DESIGN

The conceptual demonstration test design is illustrated in Figure 7. The demonstration plan consisted of first verifying that the hardware was properly recording vehicle dynamic and static properties for use in subsequent tests. The second test consisted of demonstrating/validating the impact models. Field measurements of site impacts were used to assess impact model performance. The third test consisted of installing tracking units on multiple vehicles during a single live training event. Upon completion of the training event, vehicle dynamic properties and locations were used to predict impacts along vehicle paths. The fourth test consisted of installing tracking units on multiple vehicles during multiple live training events. Data were summarized to address one or more installation identified land management issues. This test determined the ease of system use and determined the applicability of the VDMTS unit to land management decision making.

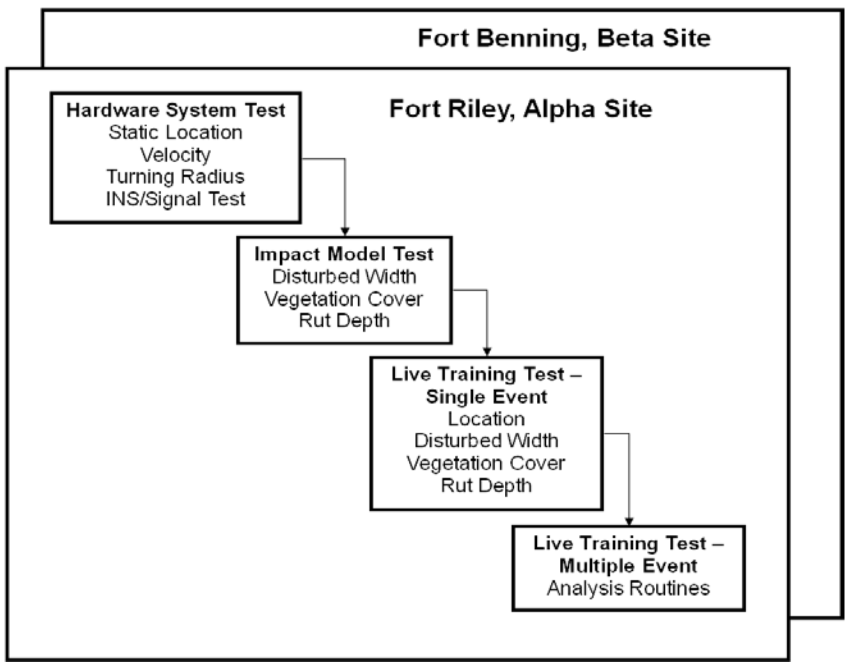

Figure 7. Conceptual demonstration plan.

6.2 BASELINE CHARACTERIZATION AND PREPARATION

Baseline characterization and preparation was essentially the first test in the conceptual demonstration plan (Figure 7). Baseline characterization consisted of verifying that the hardware functioned properly and recorded vehicle dynamic and static properties for use in subsequent tests. Tests were conducted for location, velocity, turning radius accuracy, and GPS signal loss (forcing INS system performance). These baseline tests were performed at the University of Tennessee and the methods used are described in the following section.

6.3 DESIGN AND LAYOUT OF TECHNOLOGY AND METHODOLOGY COMPONENTS

6.3.1 VDMTS Hardware Positional Accuracy Test

VDMTS systems were located on a known benchmark (assumed location truth) and allowed to collect a minimum of GPS position data, Universal Time Coordinated (UTC), and Horizontal Dilution of Precision (HDOP) for at least 6 hours. The data were transferred from the log files to spreadsheet files for data analysis. The position data were converted to the Universal Transverse Mercator (UTM) coordinate system for analysis. The average position for the GPS points is determined by finding the average of the Northing and Easting coordinates. The position error (in meters) for each point was calculated. The average of the position errors was determined and recorded.

6.3.2 VDMTS Hardware Velocity Accuracy Test

The VDMTS tracking units were mounted on a vehicle that was driven at three different but constant velocities along a track of known GPS coordinates. The velocity of the vehicle was determined by timing the vehicle with a stopwatch over a predetermined distance. The timed velocity was assumed to be truth. The velocity was also calculated from GPS/INS data by determining the change in position data of the vehicle. The same three controls used in the location test were also used in the velocity test for comparison purposes.

6.3.3 VDMTS Hardware Turning Radius Accuracy Test

The VDMTS tracking units were mounted on a vehicle that was driven around several constant radius courses (differing radii) and along a straight path multiple velocities. The distance from the center pivot to each of the course paths was used as the actual radius (truth) and was compared to the radius values calculated from the position data provided by the units. The same three controls used in the location test were also used in the velocity test for comparison purposes.

6.3.4 VDMTS Hardware INS System Test

The INS subsystem of the VDMTS tracking system is designed to ensure vehicle location and dynamic property values during periodic GPS signal loss or loss of GPS signal quality. The same three controls used in the location test were used in the velocity test for the same comparison purposes. Tracking units were mounted on a vehicle that is driven through tunnels, vegetation, and other areas of poor or no GPS signal. The location, velocity, and turning radius along the course with and without signal were recorded.

6.4 FIELD TESTING

6.4.1 Controlled Impact Model Validation Study

A series of field studies was conducted using multiple vehicles (M1A1 Abrams Tank, Armored Personnel Carrier [APC]-M113, M2A2 Bradley, High Mobility Multipurpose Wheeled Vehicle [HMMWV], HEMTT, and Stryker Light Armored Vehicle [LAV] III). These vehicles covered a

range of tracked (light to heavy) and wheeled vehicles (light to heavy and multiple axles). Since the impact models were designed for use with various types of vehicles and incorporate vehicle static properties (weight, track/wheel), vehicles that represent a range in vehicle static properties were appropriate for model validation testing. Each vehicle was driven on a systematically planned course (spiral) within a randomly located treatment plot (Figure 8). Each spiral course within a treatment plot consisted of a section of straight-line travel followed by a section of constantly decreasing turning radius. One spiral for each vehicle was traversed at a slow and fast velocity. A VDMTS hardware unit was mounted on each vehicle tested.

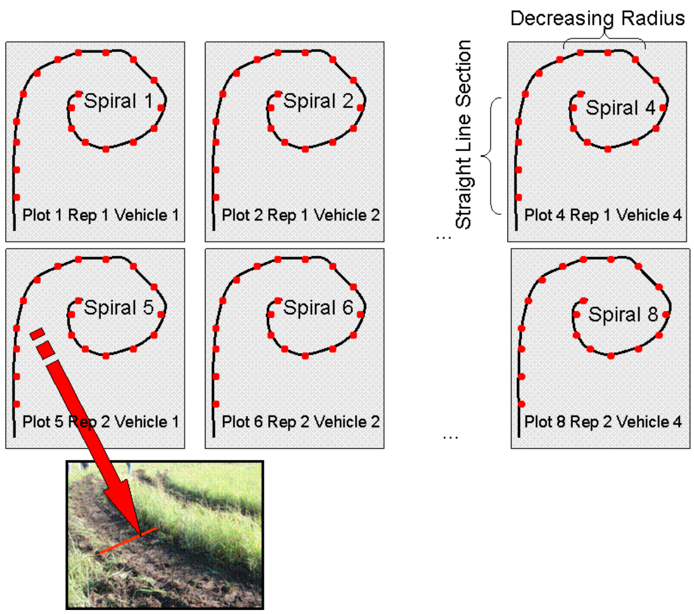

Figure 8. Controlled field test study design.
Spirals show vehicle courses. Dots show measurement plots.
Arrow shows an example of a sample point.
The line across the vehicle track illustrates a measurement transect.

6.4.2 Live Training Test – Model Validation

A field study was conducted by tracking a live training event using VDMTS systems at Fort Riley and Fort Benning. Military training events were identified through coordination with installation personnel. The military training events tracked were based on availability of units training at the installation, access to unit equipment, duration of training, number of vehicles, types of vehicles, mission doctrine, training areas scheduled, and installation objectives for study. The events included 1) four vehicle types, 2) on and off road activity, 3) wide range of site conditions utilized, and 4) 5- to 10-day durations.

A number of vehicles were instrumented (Table 2) with VDMTS hardware at both sites. Tracking units were installed in motor pool and removed after the event was completed. VDMTS data were used to locate vehicle tracks within a few days of the completion of training. Sample locations were randomly located along vehicle paths. Measurements of site damage (DW, IS, RD) were made at each sample point using methods described in Section 6.5, below. Predicted

site damage (DW, IS, RD) were compared with measured site damage to quantify the ability of VDMTS to predict overall site damage for a training event.

Table 2. Vehicles tested during live training event model validation.

Site	Test Dates	Vehicle Types Tested	# Vehicles Tested
Fort Riley	17-21 Aug 2009	HMMWV, Buffalo, Medium Tactical Vehicle (MTV)	18
Fort Benning	31 Oct - 9 Nov 2011	HMMWV, Stryker LAV III	20

6.4.3 Live Training Test – Multiple Events for System Validation

A field study was conducted by tracking a series of live training events using VDMTS systems (Table 3). A series of military training events was identified through coordination with installation personnel. The military training events tracked were based on an installation defined issue that relates to vehicle impacts on installation lands. A minimum of four training events were tracked per installation with a total of 14 events tracked over 3 years. For each training event, approximately 10-20 vehicles were instrumented and tracked depending on the training event selected and the number of vehicles in each event.

Table 3. Events tracked during multiple live training events phase of study.

Site	Test Dates	# Days	Vehicle Types	# Vehicles
Fort Riley	17-21 Aug 2009	5	HMMWV, Buffalo, MTV	18
Fort Riley	13-15 Jul 2010	3	HMMWV, MTV	7
Fort Riley	10-17 May 2011	8	HMMWV, HEMTT, Light Medium Tactical Vehicle (LMTV)	12
Fort Riley	17-22 May 2011	6	HMMWV, HEMTT, LMTV	11
Fort Benning	18-20 Oct 2010	3	Stryker, Bradley	9
Fort Benning	28-29 Mar 2011	2	Stryker, Bradley, M1A1, HMMWV	7
Fort Benning	31 Oct - 9 Nov 2011	10	Stryker, HMMWV	20
Fort Benning	9-14 Nov 2011	6	Stryker, HMMWV	22
PTA	6-9 Nov 2009	4	Stryker	3
PTA	24-29 Jan 2010	6	Amphibious Assault Vehicle (AAV)	6
PTA	17-23 Jan 2011	6	AAV	6
PTA	8-10 Jun 2011	3	AAV	2
PTA	13-14 Jun 2011	3	AAV	6
PTA	16-17 Jun 2011	2	AAV	7

6.5 SAMPLING PROTOCOL

6.5.1 Sampling Protocol for Metric Evaluation

6.5.1.1 Controlled Event Study

Vehicle impacts (i.e., DW, IS, RD) were measured immediately after tracking. DW was measured perpendicular to the vehicle track and encompassed the area where soil or vegetation was impacted by the vehicle tire track. IS was estimated using a line transect established

perpendicular to the track. A second line transect was established perpendicular to the track and adjacent to the track. For each line transect (within track and adjacent to the track), bare ground was visually estimated and reported as a percent of transect length. IS is the difference between the two values. RD was measured using a ruler laid horizontally across the outside track from undisturbed soil on the inside of the track to undisturbed soil on the outside of the track. A second ruler measured the deepest portion of the rut.

6.5.1.2 Model Validation Live Training Event Study

Primary field data collection consisted of using high quality GPS units to follow previously driven vehicle paths. Sample locations were based on the GPS location and visual location of the off-road vehicle track. This sampling allowed for an unbiased comparison of actual and predicted vegetation loss, IS, and rutting. DW, IS, and RD were measured as described above. Sample points were measured as paired sample locations within the track and outside of the track.

6.5.1.3 Multiple Live Training Event Study

A subset of the total number of events scheduled for the installation was sampled at each location. A subset of the total number of vehicles in an event was evaluated so the subset of vehicles was representative of the whole training event. This allowed data from the subset to be extrapolated to the whole event. The sampling accounted for differences in units and vehicle types. Military personnel provided input on vehicle use as related to doctrine. Natural resources personnel helped related vehicle selection to decision-making process.

6.6 SAMPLING RESULTS

6.6.1 Hardware Tests

The first component of the controlled field study demonstration plan was to validate that the hardware was properly functioning and recording vehicle dynamic and static properties for use in subsequent tests. The VDMTS system initially was the worst performing of the five systems tested (Table 4). This was because the GPS signal in the initial VDMTS system was not differentially corrected. The other units tested all used differential correction to increase the positional accuracy. A GPS system capable of Wide Area Augmentation System (WAAS) differential correction replaced the previous GPS system in the VDMTS. The static position evaluation test was repeated. Table 5 gives a summary of the test results using the upgraded VDMTS system.

Table 4. Initial position evaluation tests.

Metric	VDMTS (m)	INS/GPS (m)	G18 (m)	T132 (m)	T332 (m)
Average	7.39	4.25	2.48	1.72	0.06
CEP	6.94	2.58	2.58	1.14	0.06
2DRMS	12.13	3.90	3.90	4.55	0.10

CEP = circular error probable
2DRMS = twice distance root mean square

Table 5. Upgraded VDMTS position evaluation tests.

Metric	VDMTS (upgraded) (m)	VDMTS (initial) (m)	G18 (#1) (m)	G18 (#2) (m)	T132 (m)
Avg. error	2.05	7.39	2.11	2.75	0.28
CEP	2.00	6.94	1.89	3.04	0.20
2DRMS	3.71	12.13	3.74	4.44	0.64
Avg. HDOP	0.9	NA	1.1	1.0	1.1
Avg. SAT No.	10.5	NA	8.3	8.3	7.7
DGPS %	100	NA	100	100	100

SAT = satellite
DGPS = Differential Global Positioning System

A velocity evaluation test was performed on the VDMTS system as described in Section 6.3.2. The results from the velocity evaluation test are presented in Table 6. The truth value represents the actual measured velocity while the VDMTS values represent the VDMTS calculated.

Table 6. Velocity evaluations.

Test	Truth (m/s)	VDMTS (m/s)	Error (m/s)	Error %
1	1.43	1.47	-0.04	3.00
2	1.62	1.76	-0.14	8.64
3	1.40	1.43	-0.03	2.19
Average	**1.48**	**1.55**	**-0.07**	**4.80**

Accuracy of turning radius was measured by mounting the units on a cart pushed at two velocities on the track with a range of known turning radii as described in Section 6.3.3. The data collected are illustrated in Figure 9 with the results summarized in Table 7.

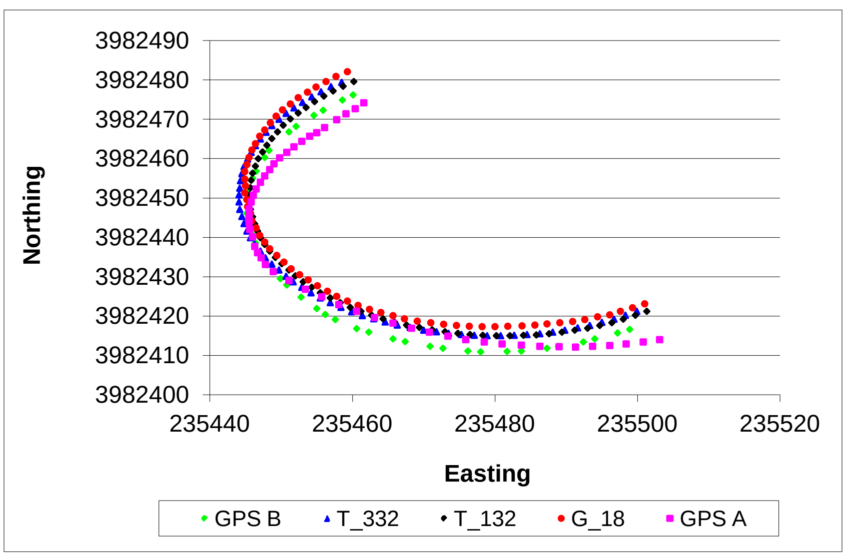

Figure 9. Turning radius evaluation tests.

Table 7. Turning radius evaluation tests.

Velocity	Actual TR (m)	VDMTS (m)	INS/GPS (m)	G18 (m)	T132 (m)	T332 (m)
Slow	6.7	6.5	4.0		4.0	
Slow	10.5	10.8	6.7		6.1	
Slow	18.6	20.0	10.9		14.1	
Slow	38.0	62.3	54.0	53.8	62.0	49.7
Slow	48.0	48.4	59.0	47.2	65.8	72.3
Fast	38.0	49.4	39.8	48.8	38.9	39.3
Fast	48.0	58.5	46.1	55.3	50.2	54.4

The final success criteria for the first performance objective was to determine ability to record in situations when GPS signals were not available due to topography, vegetation, and related conditions. This was tested by driving the unit through a tunnel and under canopy. Results show that the INS data collected from the Vehicle Dynamics Monitor (VDM) hardware increase the accuracy when compared to systems without INS capability (Table 8).

Table 8. Positional error under heavy cover test.

GPS System	Average Distance Error (m)	Standard Deviation (m)
Trimble (without INS)	2.7	0.25
Garmin (without INS)	2.7	0.34
VDM	2.2	0.17

6.6.2 Controlled Test Model Validation

The main objective of the controlled test was to validate that the impact models accurately predicted site impacts based on vehicle dynamic properties. Tests conducted included DW, vegetation loss, and RD measurements. These tests were performed using multiple vehicles at Fort Riley, PTA, and Eglin AFB. The theoretical model results were compared with measured impact values. Additionally, measured impact values were used to develop site, vehicle, and condition specific statistical models (Figure 10). These statistical models represent the best prediction possible with the variability observed and are a current method of impact assessment.

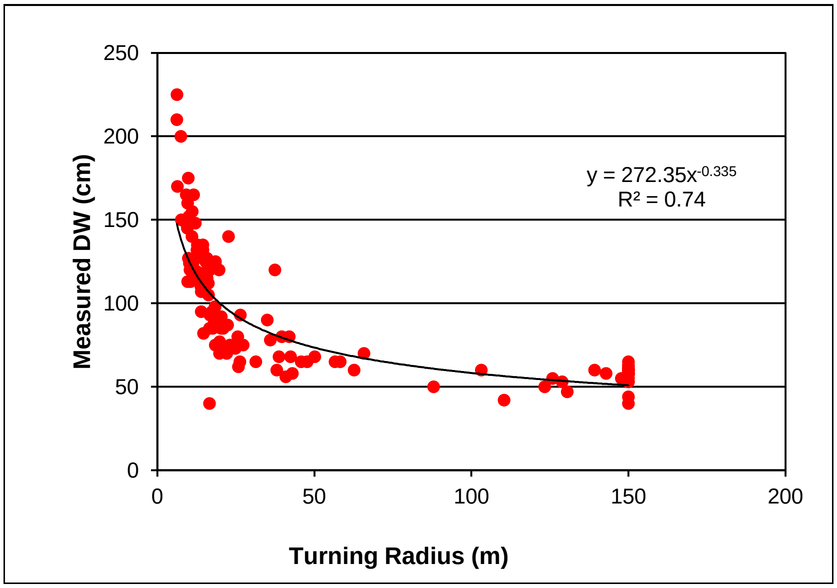

Figure 10. Example of statistical regression model developed for Stryker vehicle at PTA.

A linear regression of the predicted versus measured data was performed to determine the closeness to a unity slope. Using this as an indicator of model quality, the DW statistical model performed slightly better than the theoretical model at Eglin AFB and PTA but not at Fort Riley (Figures 11-13). Using linear regression as an indicator of model success, the statistical IS (vegetation removal) models slightly outperformed the theoretical models for the controlled studies (Figures 14-16). Given the intended use of the models, a more appropriate measure of model validation is the average error between the predicted and measured impacts using each model (Table 9).

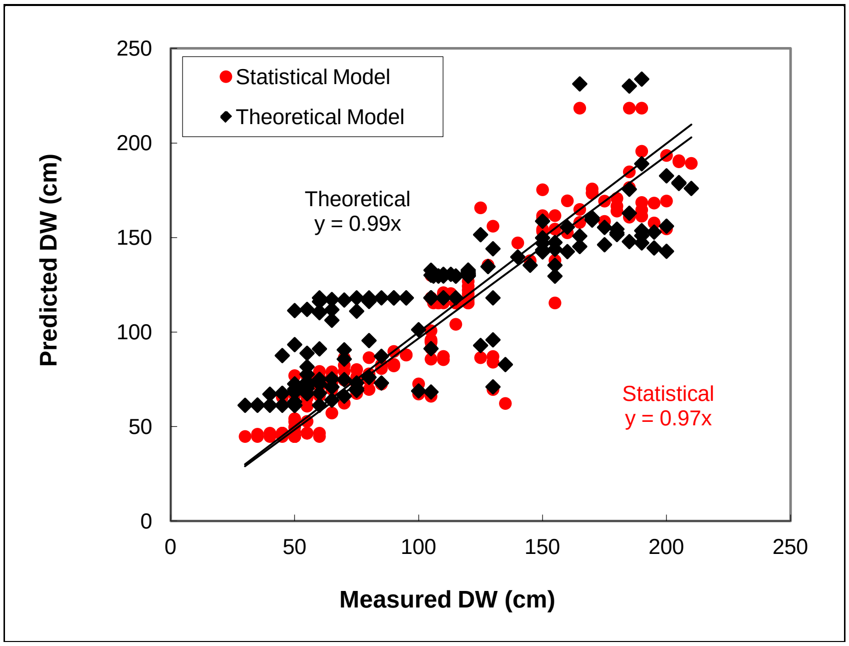

Figure 11. Theoretical and statistical model predicted DW values compared with measured values for Fort Riley controlled study.

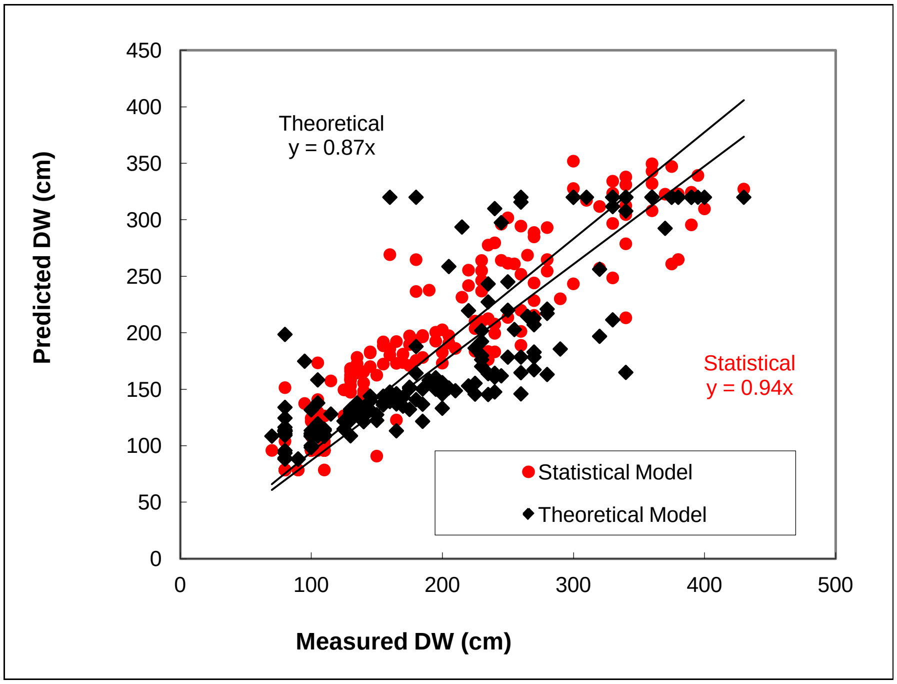

Figure 12. Theoretical and statistical model predicted DW values compared with measured values for Eglin AFB controlled study.

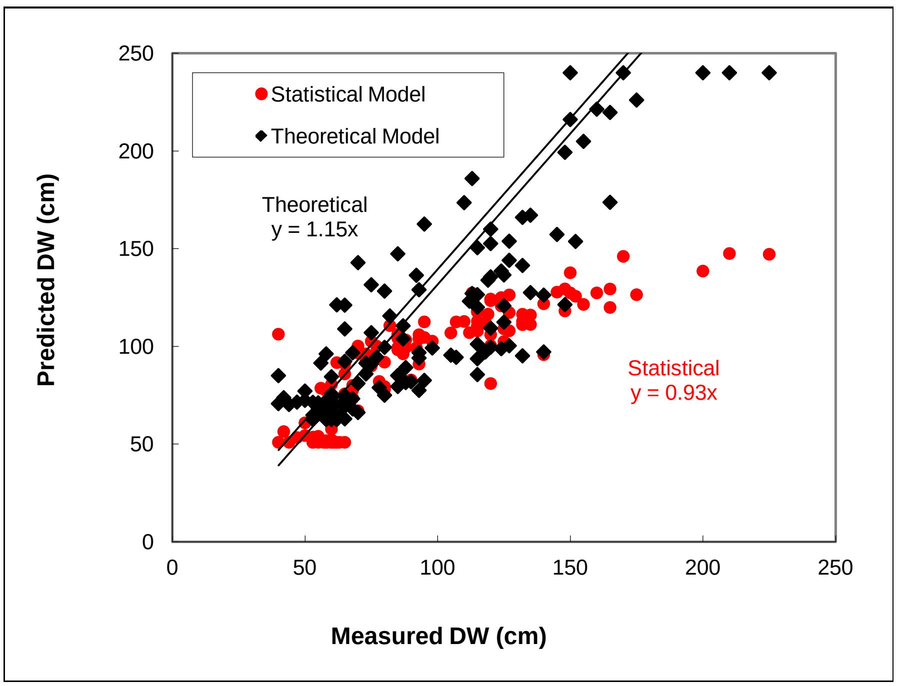

Figure 13. Theoretical and statistical model predicted DW values compared with measured values for PTA controlled study.

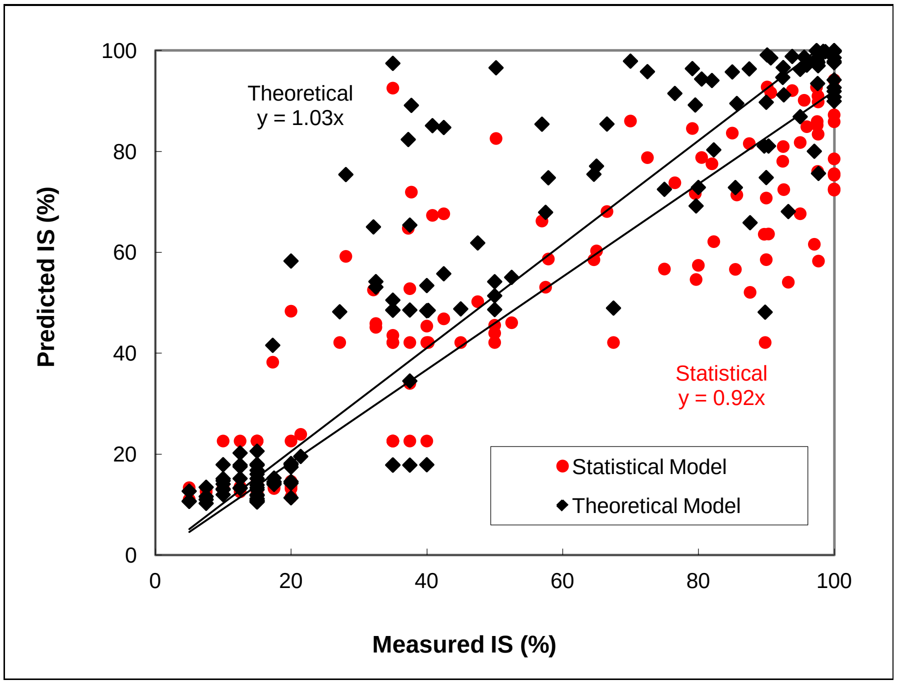

Figure 14. Theoretical and statistical model predicted IS values compared with measured values for Fort Riley controlled study.

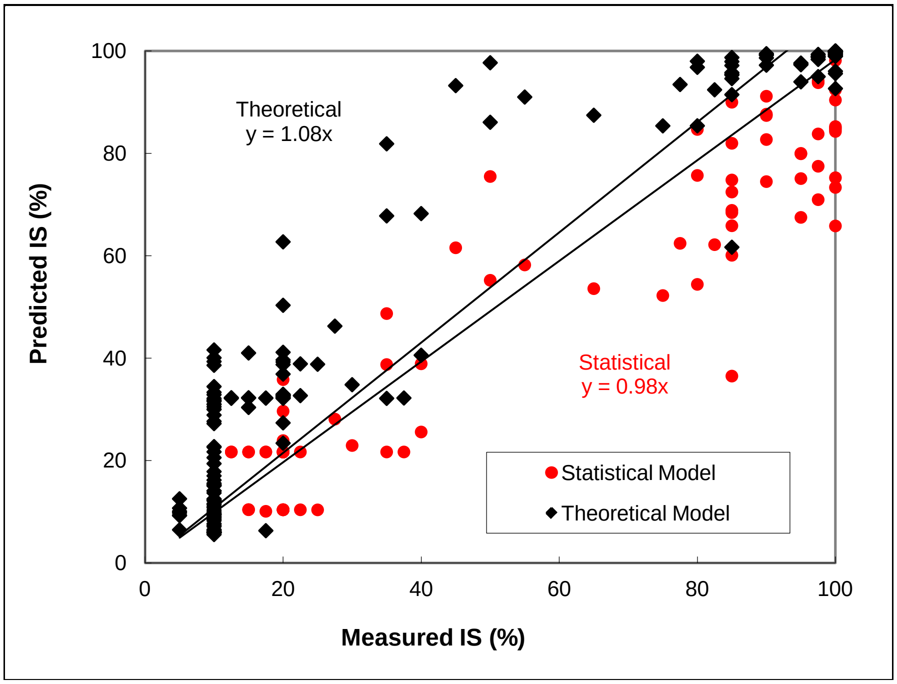

Figure 15. Theoretical and statistical model predicted IS values compared with measured values for Eglin AFB controlled study.

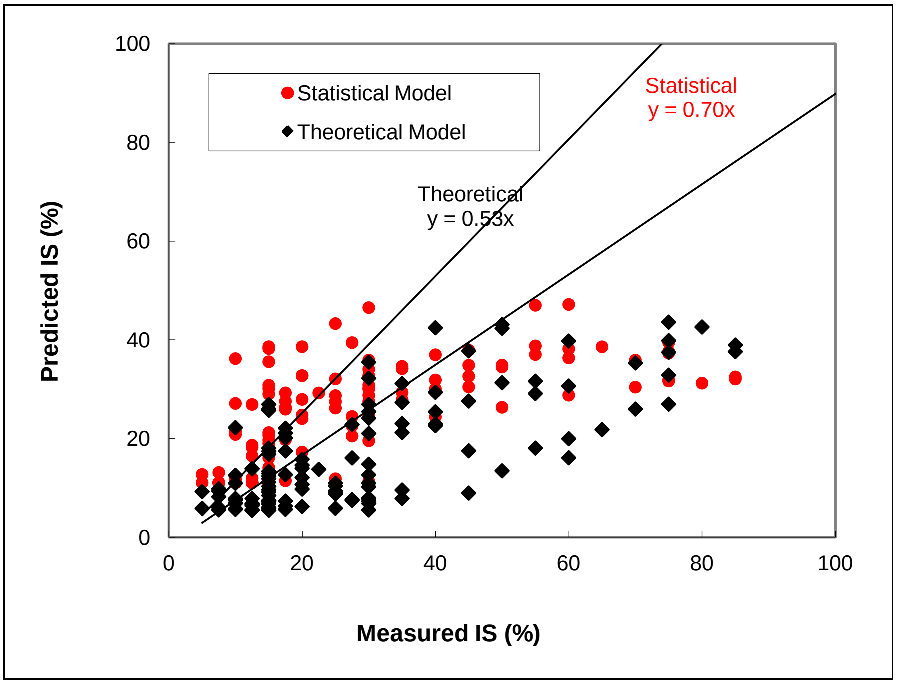

Figure 16. Theoretical and statistical model predicted IS values compared with measured values for PTA controlled study.

Table 9. Average absolute error between predicted and measured values for theoretical and statistical models.

(Note: Units are cm for DW, RD and percentage for IS)

		Riley			Eglin AFB			PTA		
		DW	**IS**	**RD**	**DW**	**IS**	**RD**	**DW**	**IS**	**RD**
Theoretical	Average absolute error	22.0	9.8	1.1	33.9	9.8	0.1	22.4	13.4	0.7
	Average error	-7.7	-3.7	1.0	17.4	-8.2	-0.1	-16.2	11.9	0.6
Statistical	Average absolute error	13.0	11.5	3.9	24.2	7.5	0.9	14.8	10.8	1.0
	Average error	1.5	1.9	-3.9	-0.8	0.5	-0.9	2.3	3.3	0.1

The statistical models predicted DW and IS better than the theoretical models in five of the six instances. This observation is expected since the data were actually used to develop the statistical models in this case. A separate dataset would need to be collected to assess unbiased statistical model performance under the controlled study.

6.6.3 Single Live Training Event Study and Model Validation

VDTMS hardware and models were tested in live training events by tracking a live training event at Fort Riley and Fort Benning. Measured impacts from these tracks were compared with model predicted values. The statistical models developed at both sites were also used to predict impacts (Figures 17-20). Even though the regression between predicted and measured was not as good for the live event study, the average absolute errors for the theoretical models in the live training event study are comparable to the errors measured in the controlled study (Table 10).

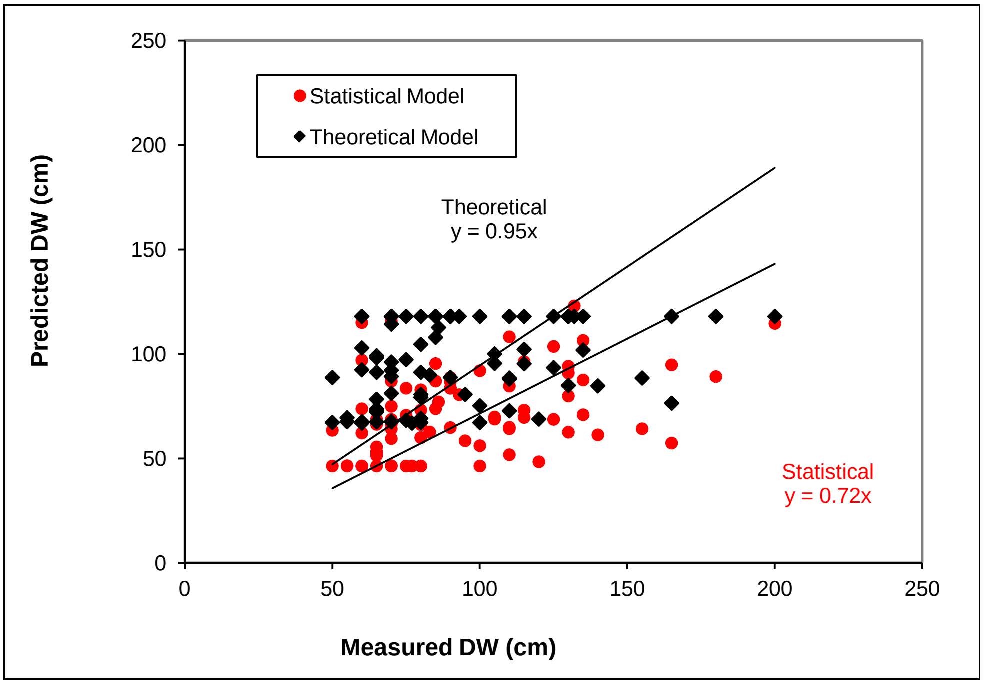

Figure 17. Theoretical and statistical model predicted DW values compared with measured values for Fort Riley live training event study.

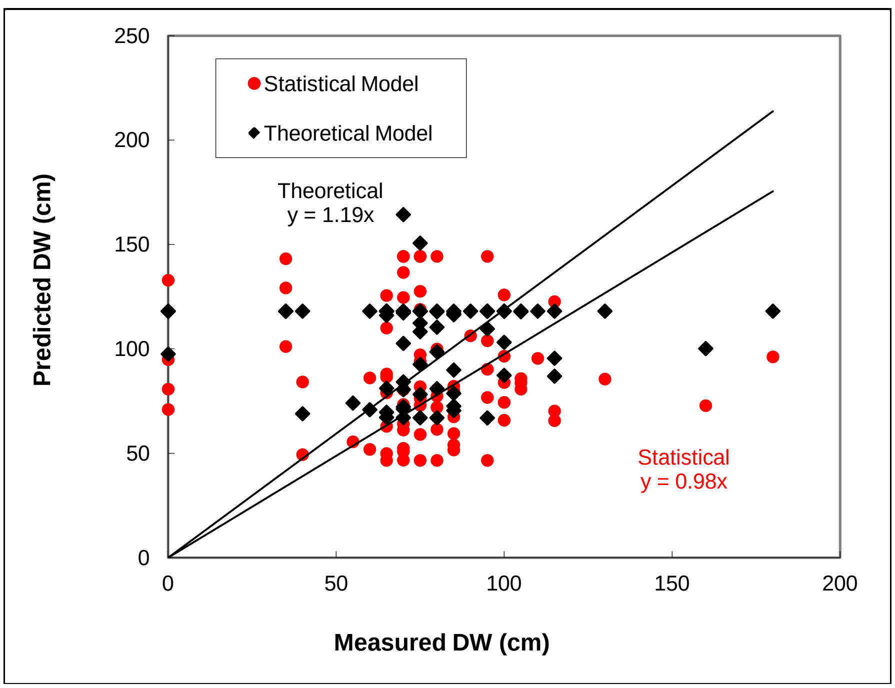

Figure 18. Theoretical and statistical model predicted DW values compared with measured values for Fort Benning live training event study.

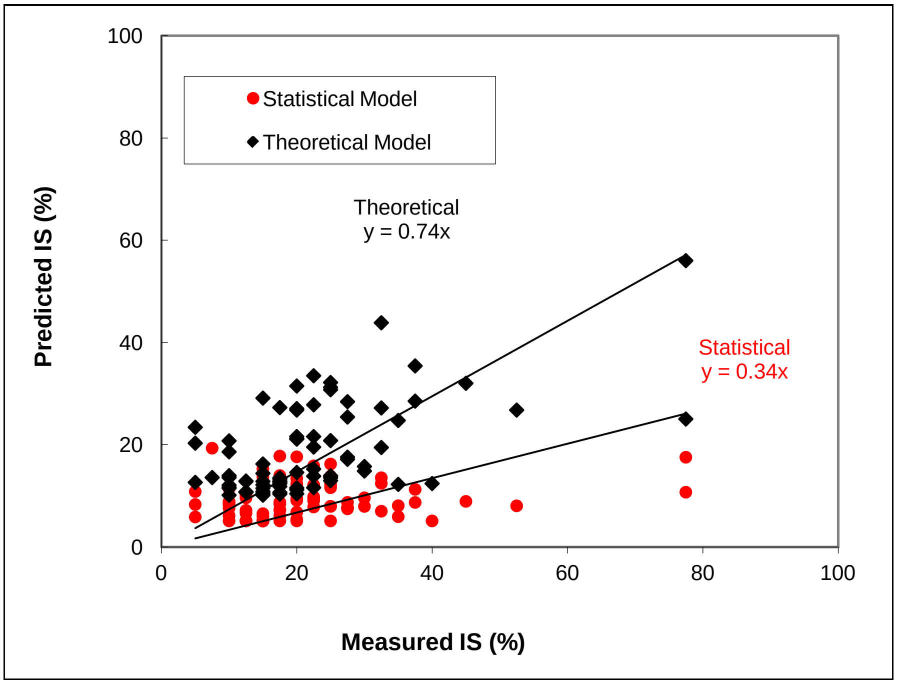

Figure 19. Theoretical and statistical model predicted IS values (vegetation removal) compared with measured values for Fort Riley live training event study.

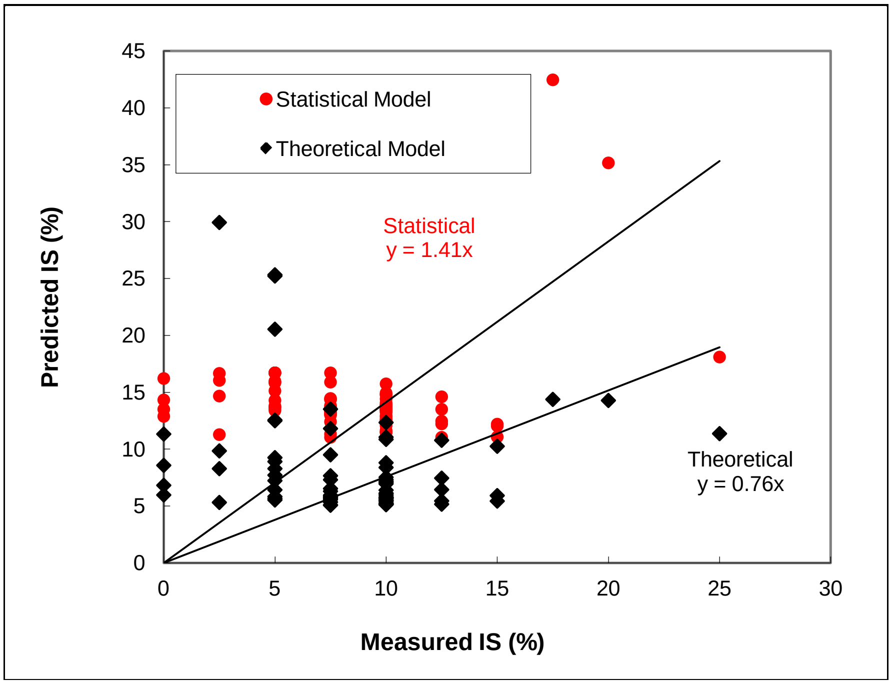

Figure 20. Theoretical and statistical model predicted IS values (vegetation removal) compared with measured values for Fort Benning live training event study.

Table 10. Absolute average errors between predicted and measured impacts for live training events.

	Fort Riley			Fort Benning			Combined		
	DW	**IS**	**RD**	**DW**	**IS**	**RD**	**DW**	**IS**	**RD**
Theoretical	24.8	7.7	0.7	34.8	4.9	0.0	29.7	6.3	0.4
Statistical	27.2	12.9	0.9	32.6	6.4	0.5	29.7	8.3	0.7

While the statistical models performed better than the theoretical models in the controlled study, the theoretical models performed as well as statistical models in the live single training event study. In practice, this means that the theoretical models may perform as well as site-specific statistical models in estimating impacts from a military training event.

In addition to modeling performance, hardware durability and positional accuracy were assessed in the single live training event tests. Table 11 summarizes the total training time, recorded time, and percent of total training time for each training event.

Table 11. Summary of hardware durability (training time recorded) from single live training events.

Installation	Total Time (hr)	Recorded Time (hr)	% Recorded
Fort Riley	1800.0	1489.1	82.7
Fort Benning	209.6	209.7	100.0
PTA	628.0	556.0	88.5
TOTAL	**2637.6**	**2254.8**	**85.5**

The positional accuracy was calculated by comparing the location of the tracks in the field with the VDMTS collected data at Fort Riley and Fort Benning. At Fort Riley, the positional accuracy observed was 1.6 m (±0.1 m). The positional accuracy observed at Fort Benning was 1.1 m (±0.1 m). To quantitatively assess INS performance without GPS signal, data were analyzed with and without INS data being forced to the GPS signal. This allowed a measurement of INS data error compared with the GPS signal. A subset of 10 out of the 38 single live training event vehicle files (48,259 sampling points) was analyzed for INS performance. In the subset of 10 vehicles, the positional accuracy never exceeded the 10 m threshold signifying the success criterion was met. The average error compared with the GPS signal was 0.164±0.002 m. Across the 48,259 samples, the maximum error compared with the GPS signal was 2.60 m.

6.6.4 Multiple Live Training Event Tests

6.6.4.1 <u>Multiple Live Training Event Hardware Durability</u>

Hardware durability was assessed through measuring the percent of each training event that was recorded by the vehicular tracking systems. Any loss of data was attributed to hardware error (e.g., hardware breakage, power failure, data card fault, loss of hardware). Table 12 summarizes the total time recorded and total training time recorded for each event. A total of 13,587.1 hr of data was recorded out of 15,056.8 hr of total training time during which the units were mounted

(90.2±2.5%). In addition, recorded time was analyzed by vehicle type to determine if hardware durability is a function of vehicle type (Table 13). Except for the HEMTT, over 80% of the data were recorded for each vehicle.

Table 12. Hardware durability performance by event (% of training time recorded).

Installation	Date	# Vehicles	Total Time (hr)	Recorded Time (hr)	% Recorded
Fort Riley	17-21 Aug 2009	18	1800.0	1489.1	82.7
Fort Riley	13-15 Jul 2010	7	332.6	250.9	77.8
Fort Riley	10-17 May 2011	12	2108.2	1682.6	79.8
Fort Riley	17-22 May 2011	11	1515.9	1225.6	80.8
Fort Benning	18-20 Oct 2010	9	519.5	519.2	99.9
Fort Benning	28-29 Mar 2011	7	209.6	209.7	100.0
Fort Benning	31 Oct - 9 Nov 2011	20	4215.2	3998.6	94.9
Fort Benning	9-14 Nov 2011	22	2700.3	2700.3	100
PTA	6-9 Nov 2009	3	86.9	86.9	100
PTA	24-29 Jan 2010	6	509.9	471.8	92.5
PTA	17-23 Jan 2011	6	628.0	556.0	88.5
PTA	8-10 Jun 2011	2	49.2	49.2	100.0
PTA	13-14 Jun 2011	6	171.3	143.6	83.8
PTA	16-17 Jun 2011	7	220.2	2	92.5
	TOTAL	**139**	**15056.8**	**13587.1**	**90.2±2.3**

Table 13. Hardware durability performance by vehicle type (% of training time recorded).

Vehicle	Type	Number Vehicles	Total Time (hr)	Recorded Time (hr)	% Recorded
HMMWV	Wheeled	59	8085.6	7597.9	93.9±2.9
MTV	Wheeled	7	649.4	550.5	84.8±11.3
Buffalo	Wheeled	1	71.9	71.9	100.0±0.0
Stryker	Wheeled	18	1785.2	1785.2	99.98±0.0
Bradley	Tracked	6	289.7	289.7	100.0±0.0
AAV	Tracked	26	1578.6	1424.2	90.2±4.6
Abrams	Tracked	1	30.1	30.1	100±0.0
HEMTT	Wheeled	12	1881.4	1181.2	62.79±13.9
LMTV	Wheeled	4	626.4	626.4	100.0±0.0

6.6.4.2 Multiple Live Training Event Ease of Use

A second objective of the multiple live training event demonstration was to assess the time requirements for implementing the VDMTS process. As described in Section 6.4.3, the time required for training technicians on each step of the VDMTS as well as time required to perform each step were recorded. Table 14 documents the number of technicians trained for each step and the training time required for each step. Table 15 exhibits the time required to perform each step of the VDMTS process and summarizes the number of vehicles and events for which these data were collected.

Table 14. Training times for each step of VDMTS implementation for ease-of-use assessment.

	Ease-of-Use - Training Times		
	Hardware Use	Data QA/QC	Analysis
# Technicians trained	16	6	6
Average time (hr)	0.3	1.07	6.33
Standard deviation (hr)	0.12	0.11	0.82
Standard error (hr)	0.23	0.35	2.58

Table 15. Performance times for each step of VDMTS implementation for ease-of-use assessment.

	Ease-of-Use - Performance Times		
	Equipment Setup/Removal (hr/vehicle)	Data QA/QC (hr/vehicle file)	Analysis (hr/event)
# Vehicles	136	136	136
# Events	14	14	14
Average time (hr)	0.19	0.82	5.45
Standard deviation (hr)	0.11	0.24	3.57
Standard error (hr)	0.01	0.02	0.95

7.0 PERFORMANCE ASSESSMENT

7.1 CONTROLLED FIELD STUDY – ACCURATE VDMTS HARDWARE MEASUREMENT

The success criteria assigned to the position evaluation test was vehicle positional accuracy within 5.0 m (15.4 ft) 95% of the time. The upgraded VDMTS units met the success criteria. The 6-hr static positional test for the upgraded unit resulted in an average error of 2.05 m with 99.87% of the data points within 5.0 m of the actual location, exceeding the success criteria established. A velocity evaluation test was performed on the VDMTS system. The success criteria assigned to this test was vehicle velocity within 2.24 m/s (5 mph) 95% of the time. The VDMTS calculated velocity was compared to the actual velocity. Three tests were performed and the VDMTS was well within the criteria at all times. The velocity evaluation resulted in a velocity within 2.24 m/s (5 mph) of the true value for 100% of the data points.

The success criteria for the turning radius evaluation test was turning radius within 10 m 95% of the time. The results are given in Table 7. While the VDMTS did not predict the turning radius within 10 m for 95% of the time at both velocities, it was within 10 m of the high accuracy, high cost system (the best prediction available) for 95% of the test. It is interesting to note that the unit was more accurate at predicting small lower turning radii (sharper turns). Since vehicle impacts increase with decreasing turning radii, the VDMTS unit should allow for accurate impact prediction. Even though turning radius prediction errors increased with increasing turning radii, the associated impact prediction error is small since lower impacts are observed in these conditions. Although the VDMTS hardware did not explicitly meet the success criteria established, it performed as well as alternative high accuracy systems, indicating metric success.

The final success criteria for the first performance objective was to determine the ability to record in situations when GPS signals were not available due to topography, vegetation, and related conditions. The VDMTS met the performance metric that VDMTS hardware with INS provides more accurate dynamic vehicle properties than GPS alone.

7.2 CONTROLLED FIELD STUDY – ACCURATE VDTMS IMPACT MODEL PREDICTIONS

The success criteria assigned to the model validation phase of the demonstration for DW is a correlation between predicted and measured values of 0.8 or higher, and 95% of the predicted values are within 20 cm of the actual value. For vegetation loss (IS) the success criteria were a correlation between predicted and measured values of 0.7 or higher, and at least 95% of the values within 20% vegetation removal accuracy. The criteria set for RD accuracy were a correlation greater than 0.6 and 95% of the points within 3.0 cm of the observed RDs. A summary of the results from the controlled study at each location is given in Table 16. The success metric was generally met for correlation between predicted and measured values for DW and IS. For DW, only 50% of the samples were within the 20 cm threshold. The theoretical IS model met the success criteria established. While the RD model met the percent samples within defined metric, it did not meet the correlation between predicted and measured metric.

When analyzing the data, it became apparent that the amount of variability experienced in measuring impacts was underestimated when establishing the metrics. In a validation project, metrics are established to compare results against some value to determine success or failure. In this case, somewhat arbitrary metrics had been established based on some previous data collected. A better estimation of the theoretical model validity may be comparing results against an existing method of predicting impacts. Prior to the development of the theoretical models, a statistical regression model could be developed for a specific site/vehicle combination based on a field study similar to the controlled study. This empirical model could be considered the best prediction of impacts given the variability experienced in the field.

As a secondary measure of theoretical model success, statistical regression models were developed for each site/vehicle combination. It is important to note that these results are biased towards the statistical models since they were developed using the same dataset used for the metric evaluation. The statistical DW model slightly outperforms the theoretical model; however, it is not close to meeting the metrics established (Table 16). Theoretical model performance was very comparable to the statistical models (Tables 16-17).

Table 16. Metric Analysis summary for theoretical and statistical models in Fort Riley, Eglin AFB, and PTA Controlled Study.

(Note: Units are cm for DW, RD and percentage for IS)

	DW		IS		RD	
	Theoretical	Stat_Mod	Theoretical	Stat_Mod	Theoretical	Stat_Mod
Correlation between predicted and measured	0.89	0.94	0.90	0.90	0.1	0.5
Average error between predicted and measured	-0.2 cm	2.7 cm	-1.3%	1.7%	0.5 cm	-1.4 cm
Average absolute error between predicted and measured	28.0 cm	18.8 cm	10.8%	9.7%	0.6 cm	1.8 cm
% Samples within defined metric	50%	67%	86%	78%	94%	85%

Table 17. Average absolute error between predicted and measured values for theoretical and statistical models from controlled study.

(Note: Units are cm for DW, RD and percentage for IS)

	Riley			Eglin AFB			PTA			Combined		
	DW	IS	RD	DW	IS	RD	DW	IS	RD	DW	IS	RD
Theoretical	22.0	9.8	1.1	33.9	9.8	0.1	22.4	13.4	0.7	28.0	10.8	0.6
Statistical	13.0	11.5	3.9	24.2	7.5	0.9	14.8	10.8	1.0	18.8	9.7	1.8

7.3 SINGLE LIVE TRAINING EVENT – ACCURATE VDMTS HARDWARE MEASUREMENTS

Single live training events were tracked at Fort Riley and Fort Benning. A total of 38 vehicles was tracked across those two events representing four vehicle types. The positional accuracy met the metric criteria with an off-road positional accuracy observed of 1.6 m (±0.1 m). In several

instances during the live training event at Fort Riley, the GPS signal was lost. In these cases, the VDMTS INS system succeeded in calculating vehicle location. To assess INS performance, data were analyzed on a subset of the vehicle files with and without the GPS data (48,259 samples). The success criteria for this metric was vehicle positional accuracy within 10 m (32.8 ft) for 300 m (984.2 ft) after GPS signal was lost 90% of time. In the subset of 10 vehicles, the positional accuracy never exceeded the 10 m threshold signifying the success criteria were met. The average error compared with the GPS signal was 0.164±0.002 m. Across the 48,259 samples, the maximum error compared with the GPS signal was 2.60 m.

7.4 SINGLE LIVE TRAINING EVENT – ACCURATE VDTMS IMPACT MODEL PREDICTIONS

The success criteria established for this test was predicted DW within 20 cm of actual DW in 90% of the sample sites, predicted vegetation loss within 20% of actual vegetation loss in 80% of the sample sites, and predicted RD within 4 cm of actual RD in 80% of the sample sites. As discussed in Section 6.6.3, the predictions from the statistical regression models were also compared against the success metrics to estimate the accuracy of the theoretical models compared to the previous method of predicting impacts. The data summarized against these metrics are given in Table 18.

The metrics established for IS and RD were met (IS within 20% and RD within 4 cm of the actual values for at least 80% of the sampling sites) while the metric established for DW did not meet the established metric (<90% of the data within 20 cm of actual DW). However, the average absolute error between the predicted and measured values for DW was the same when predicted with the theoretical model and the site and vehicle-specific statistical model (29.7 cm versus 29.8 cm). While the statistical models performed better than the theoretical models in the controlled study, the theoretical models' performance was similar to the statistical models in the live single training event study. In fact, the theoretical model performed better than the site and vehicle-specific statistical model in predicting IS. Previously, a separate study was required to develop a statistical model for each site being tested, resulting in added study costs. The theoretical model removes this necessity while providing an estimate of the training event impacts.

Table 18. Summary of live training event tracking at Fort Riley and Fort Benning (combined).

	DW		IS		RD	
	Theoretical	Stat_Mod	Theoretical	Stat_Mod	Theoretical	Stat_Mod
Average error between predicted and measured	14.9 cm	-6.1 cm	-1.8%	-1.7%	0.1 cm	-0.2 cm
Average absolute error between predicted and measured	29.7 cm	29.8 cm	6.3%	8.3%	0.7 cm	0.9 cm
% Samples within defined metric	45.6%	50.6%	95.0%	93.1%	98%	100%

7.5 SINGLE LIVE TRAINING EVENT – VDMTS HARDWARE DURABILITY

The last component of the single live training events was to assess hardware durability. The success metric established for this study was percent of recorded time >80% of the actual military training time. Hardware durability in single events was assessed at Fort Riley, Fort Benning, and PTA. From Table 11 in Section 6.6.3 we can see that this metric was met at all three locations with a total percent data recorded of 85.5% across the three events.

7.6 LIVE TRAINING – VDMTS HARDWARE DURABILITY

The hardware durability described in the previous section was also assessed across all training events in the last phase of the demonstration. For this assessment, the success criteria established was percent of recorded time >80% of training time per vehicle type for any event. The demonstration resulted in 13,587.1 hr logged out of a total of 15,056.8 total hr of training resulting in VDMTS units recording 90.2% (±2.3%) of the total training events tracked. In every event but two, >80% of the data were collected (77.8% and 79.8% on July 13-15, 2010, and May 10-17, 2011, respectively). Separating the data by vehicle type, >80% of the data were collected except for the HEMTT vehicle (62.8±6.9%). The reason for more data loss on the HEMTT vehicles is unclear. This could be due to the mounting location available for the HEMTT. While the failure of data collection on the HEMTT is cause for some concern, the influence on the total off-road impacts is minor. In 14 training events tracked, very few HEMTTs were observed going off-road. A lesson learned from these demonstrations was that care should be taken to ensure that the units are mounted as securely as possible, especially when mounting units on the HEMTT vehicles.

7.7 LIVE TRAINING – QUANTITATIVE EASE OF SYSTEM USE

The system ease of use was measured quantitatively by determining the time required to perform each task and compare with a time deemed acceptable in the approved demonstration plan. The success criteria were developed through discussion with installation staff and ESTCP management. In the demonstration plan, the success metric established for time required for analysis was 40 hr per five events at each installation. Since we were not able to track five events at both installations, the success metric was modified to 8 hr per event to account. The success metrics and times required for each task are given in Tables 19 and 20. In every case, the system met the success metrics established ($p<0.05$). This indicates the system was simple enough for easy implementation into the management program without extensive training or time requirements.

Table 19. Training summary for ease of system use assessment.

	Hardware Use (hr/person)	Data QA/QC (hr/person)	Analysis (hr/person)
Success criteria (H_0)	4.0	4.0	16.0
Average time (hr)	0.3	1.07	6.33
Standard error (hr)	0.23	0.35	2.58
T-test (average time <success criteria)	$p<0.0001$	$p<0.0001$	$p<0.0001$

Table 20. Summary of time requirement to perform each step in the VDMTS process.

	Equipment Setup/Removal (hr/vehicle)	Data QA/QC (hr/vehicle file)	Analysis (hr/event)
Success criteria (H_0)	1.0	1.0	8.0
Average time (hr)	0.19	0.82	5.45
Standard error (hr)	0.01	0.02	0.95
T-test (average time <success criteria)	p<0.0001	p<0.0001	p=0.00958

7.8 LIVE TRAINING – QUANTITATIVE QUALITY AND ACCURACY OF DATA

This performance objective was designed to test the hardware and model components' ability to produce actionable results for installation land managers. The first metric objective was to assess the ability to use the data for parameterization of land management models. The resolution of each specific model defines the acceptable accuracy of data for model parameterization. As described in Table 1, a success criteria of <10 m positional error is established. Success criteria for time off-road, vegetation loss, and IS are errors less than 20%. The methods for obtaining these criteria are described in Table 1.

The observed accuracy in this demonstration for each data type are 1.6 m average positional error, 1% error in estimating time off-road and 6.3% error predicting IS. These measured accuracies meet the proposed success criteria for each data type. These values also allow determination of the ability to use this system to parameterize different models. If the model requires vehicle tracking data and uses a spatial resolution of 3 m, the accuracy of these data for model use is adequate. However, if an erosion prediction model required 5% accuracy of vegetation cover for acceptable results, data quality from the VDMTS process (hardware and models) is not high enough for implementation in the model.

The second metric objective was to determine if VDMTS data quality is sufficient to identify training area use patterns. Vehicle positional accuracy required for LRAM and other maintenance requirements was determined to be <10 m positional error. For TES habitat impact analysis, a <5 m positional error is required. Additionally, <20% error in vegetation removal is needed for site maintenance requirements. The development of these success criteria is documented in Table 1. The observed accuracy in this demonstration for each data type is 1.6 m average positional error and 6.3% error in vegetation loss estimation. These measured accuracies meet the proposed success criteria for each data type. Again, this approach can be taken to determine if data quality is acceptable for any training area use pattern quantification and analysis.

7.9 LIVE TRAINING – QUALITATIVE EASE OF SYSTEM USE

In addition to quantitative ease-of-use metrics, a qualitative ease-of-use metric was proposed in the demonstration plans. This was aimed at determining if the effort required to train a technician in VDTMS operation and performance of tracking events and data analyses was acceptable. The qualitative metric was also proposed to obtaining any feedback from the installation technicians on use of the systems to identify any drawbacks to the system and learn from any suggestions they may have.

This metric was tested by giving an evaluation form to each technician who used the system in the demonstration. For each step of the data collection, they were asked to give a 1-10 rating (a rating of 10 indicates no issues with that step while a rating of 1 indicates an unusable or difficult step. The results of these evaluation forms are given in Table 21. We consider an average rating >7, indicating no major issues with that step in the VDMTS process.

Table 21. Summary of evaluation forms received from technicians on VDMTS use.

Task	Average Rating	Comments
Operation of vehicle tracking hardware	9.3	• Overall, VDM boxes fairly easy to use • Problems w/magnetic mounting of GPS sensor
Mounting and dismounting of hardware	8.7	• Some issues mounting boxes to vehicles (i.e., finding secure place to mount without getting in way) • Hardware needs to be placed securely and oriented correctly
Hardware maintenance (e.g., charging/replacing batteries, data card replacement, etc.)	9.5	• New units easier to charge than older models (pre-demonstration)—however, would be nice to have better access to data card
Downloading data	10	
Checking data on computer for errors and completeness	8.5	
Processing raw data files	7	• Process is straightforward and simple but takes time to complete if many vehicles
Processing data to determine vehicle velocity and turning radius	8	
Using vehicle impact models for prediction of impacts	7	
Analyzing impact data for site specific summaries	8	

Overall, the results of the qualitative ease of use metric indicated that vehicle tracking units were easy enough for the technicians to work with. There were a few comments and concerns that can be addressed in the systems in the future. Since the VDM units are a custom built product, it is possible to request certain component changes if requested by an installation.

7.10 LIVE TRAINING – QUALITATIVE QUALITY AND ACCURACY OF DATA

A similar qualitative metric was proposed to assess quality and accuracy of data for land use decision making. This metric was proposed to document issues and comments installation technicians had regarding implementing the VDMTS process in their programs. Similar to the previous section, an evaluation form was given to each technician who used the system in the demonstration (See Appendix D of the Final Report for form). Technicians filled in only the evaluation sections relating to their experience with the system. A summary of the responses received in these evaluation forms is given in Table 22.

Table 22. Summary of evaluation forms received from installation land managers on use of data collected with the VDMTS.

Issue	Average Rating	Comments
Data collected are of value for decision making	9.3	• This will be very useful data for assessing impacts of heavy maneuver effects on Red-cockaded Woodpeckers (RCW) pertaining to the Army Reconnaissance Course (ARC) when providing briefings to the U.S. Fish and Wildlife Service (USFWS) and our chain of command.
Maps produced from data aid in visualization and analysis of vehicle use patterns and associated impacts	9	• This will be very useful data for assessing impacts of heavy maneuver effects on RCWs pertaining to the ARC when providing briefings to the USFWS and our chain of command.

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8.0 COST ASSESSMENT

8.1 COST MODEL

Since there is not an existing technology to compare costs, several other technology cost implementation scenarios were evaluated. The scenarios were intended to show that costs vary between installations that want to track many events from those interested in tracking only a few. The scenarios below are hypothetical scenarios. Table 25 gives the cost development approach for the scenarios.

1. Scenario 1: An installation that needs to track several events to answer one management question and then never use the technology again. This scenario is representative of an installation needing to track military vehicles to assist with an environmental impact statement or biological assessment. This scenario would track 20 vehicles for 5 one-week-long events over a period of 1 year.
2. Scenario 2: An installation that needs to continually track a certain number of events each year for an indefinite period of time. This scenario is representative of an installation needing to track military vehicles to show compliance with an established policy or agreement. This scenario would track 20 vehicles for 10 one-week-long events every year for 5 years.
3. Scenario 3: An Army regional support center provides support to all installations requiring use of VDMTS services. This could also be a contractor that provides vehicle tracking support to installations under contract. This scenario is representative of an implementation decision to support multiple installations more economically. This scenario is based on the U.S. Army Sustainable Range Program installation support model. This scenario would potentially include 10 installations that each need to track 20 vehicles for 10 one-week-long events every year for 5 years.
4. Scenario 4: Official Army weapon and training system data (e.g., DFIRST, BFT) become available to provide vehicle static and dynamic property information. For this cost analysis, we assumed that the Army users (e.g., ITAM and Environmental) would have access to these datasets. Therefore, only data analysis costs and possibly some limited data acquisition costs are required. Currently however, this assumption likely does not hold true, and acquisition costs (time and money) would be higher than assumed. For this scenario, we used the same installation requirements as Scenario 2 for comparison (20 vehicles for 10 one-week-long events every year for 5 years).

Cost elements estimates are summarized in Table 23. Cost elements are the main cost groups associated with technology use. Sub-element costs are a further breakdown of costs categories associated with a specific cost element. The intent of this table is to identify all data and information that were tracked through demonstration implementation. These data were utilized to calculate costs for each Scenario in Table 25.

Table 23. Cost model.

Cost Element	Cost Sub-element	Data Tracked
VDMTS Hardware Cost	Purchase	Initial hardware purchase cost reported as average cost per vehicle tracking unit. Initial hardware cost data collected by Cybernet during system production.
	Maintenance/ replacement	Hardware maintenance/replacement cost takes into account life expectancy and maintenance costs. Life expectancy is estimated by Cybernet. Maintenance costs include part (e.g., battery, switches, etc.) replacement and repair.
Training	Hardware	Cost of labor for person to learn how to operate and maintain hardware. Cost is based on number of hours of training per person trained and average employee cost/hr.
	Data processing	Cost of labor for person to learn data processing and data QA/QC procedures. Cost is based on number of hours of training per person trained and average employee cost/hr.
	Data analysis	Cost of labor for person to learn data analysis procedures. Cost is based on number of hours of training per person trained and average employee cost/hr.
Event Tracking	Preparation	Labor cost to maintain and prepare systems for event tracking. Includes battery recharging, minor repairs, and system performance checks. Cost based on average time per tracking unit and average employee cost/hr.
	VDMTS setup	Labor cost to install systems in the field. Cost based on average time per tracking unit and average employee cost/hr.
	VDMTS removal	Labor cost to remove systems in the field. Cost based on average time per tracking unit and average employee cost/hr.
	Data processing	Labor cost to download, perform quality control, and preprocess data. Cost based on average labor time for QA/QC preprocessing per tracking unit per event multiplied by average labor cost
	Travel	Travel cost associated with event tracking. This cost includes airfare, rental car, and per diem. This cost is estimated since travel costs vary depending on distance and location. This cost is necessary to accurately assess the different implementation scenarios.
Event Analysis	Basic summarization	Cost to perform basic analysis of vehicle tracking data. This includes performing impact assessment analysis of the vehicle tracking data with the theoretical models, incorporating data into geographic information system environment, and performing basic event summaries. Cost based on average labor time for basic vehicle impact summarization.
	Site/question-specific summary	Data interpretation/summarization to meet land management objective. This could be the percent of vegetation removal by location, percent time off-road, or amount of time vehicles spent in TES habitat. Cost based on average labor time for data interpretation/presentation for land management problem. Cost is the total personnel labor multiplied by the average labor cost.

8.2 COST DRIVERS

The cost drivers for implementing the VDMTS process and determining which application and technology is most cost effective are highly dependent on the specific situation at each installation and the issues being addressed. For example, it is anticipated that larger installations with more personnel would be able to implement the VDMTS process in-house. In contrast, a small branch (only a few people) at a smaller installation may need to hire a regional support

center to perform the analyses needed. Additionally, the cost for implementing the system depends on the issues being addressed and the data needed to answer those questions. An installation needing to track only a few events could hire a regional support center to perform the analysis required. The following section expands upon these anticipated cost drivers and provides recommendations for system implementation given different scenarios.

8.3 COST ANALYSIS AND COMPARISON

8.3.1 Monitoring Methods and Costs

A cost analysis was performed for the scenarios defined in Section 8.1 utilizing the data collected as described in Table 23. The cost data described in Table 23 were collected throughout the demonstration from a number of sources. Hardware costs were obtained from the suppliers (Cybernet, parts suppliers, etc.). Hardware maintenance costs were calculated from the costs observed throughout the demonstration. Time requirements for each component were obtained through this demonstration (Performance Objective 7). The actual life span depends on the severity of the conditions the unit is being used in, the average length of deployment, and other factors. Because the cost of implementation is highly dependent on the situation, an extensive life-cycle cost analysis is difficult without making a number of assumptions. In order to estimate life-cycle costs and yearly costs, the cost analysis approach taken is to assume the different scenarios described in Section 8.1. A life-cycle cost analysis of the hardware was performed in order to estimate a maintenance/replacement cost per event (Table 24).

Table 24. Life-cycle cost analysis of VDMTS hardware.

Life-cycle Cost Component	Cost/Unit	Replacements Required/Life Span	Cost/Life Span
Initial purchase cost	$2900.00	1	$2900.00
Battery replacement	$36.86	2	$73.72
GPS antenna replacement	$31.00	1	$31.00
Switch replacement	$7.00	2	$14.00
Wiring and connections	$20.00	2	$40.00
Misc. costs (data cards, card connectors, etc.)	$30.00	4	$120.00
	Total replacement cost		$3178.72
	Estimated unit life span (# events)		100
	Maintenance-Replacement Cost per Event per Unit		$31.79

Table 25. Cost model for alternative fielding scenarios.

Cost Element	Cost Sub-Element	Costing Analysis Scenario: Installation Performed (Scenario 1 and 2)	Regional Support Center (Scenario 3)	Army Standard System (DFIRST/BFT) (Scenario 4)
Hardware	Purchase	$2900/unit	$2900/unit	NA
	Maintenance/replacement	$32/unit/event	$32/unit/event	NA
Training	Hardware	4 hr/class@$37/hr	4 hr/class@$37/hr	NA
	Data processing	4 hr/class@$37/hr	4 hr/class@$37/hr	4 hr/class@$37/hr
	Data analysis	16 hr/class@$53/hr	16 hr/class@$53/hr	16 hr/class@$53/hr
Event Tracking	Preparation	0.5 hr/unit@$37/hr	0.5 hr/unit@$37/hr	0.0 hr/unit
	Setup	0.3 hr/unit@$37/hr	0.3 hr/unit@$37/hr	0.0 hr/unit
	Removal	0.1 hr/unit@$37/hr	0.1 hr/unit@$37/hr	0.0 hr/unit
	Data processing	1.0 hr/unit@$37/hr	1.0 hr/unit@$37/hr	1.0 hr/unit@$37/hr
	Travel	$0/event	$1500/event	$0/event
Event Analysis	Basic summary	1.0 hr/vehicle@$53/hr	1.0 hr/vehicle@$53/hr	1.0 hr/vehicle@$53/hr
	Site specific summary	8.0 hr/summary@$53/hr	8.0 hr/summary@$53/hr	8.0hr/summary@$53/hr
Total Costs	Purchase costs	$2900/unit	$2900/unit	$0
	Training costs/individual	$1144/individual	$1144/individual	$996/individual
	Fixed cost/ event	$499/event	$1999/event	$424/event
	Cost/vehicle tracked/event	$123/vehicle	$123/vehicle	$90/vehicle
	Cost for Proposed Scenarios	*Scenario 1:* $76,954 ($76,954/year/site) ($15,391 event) *Scenario 2:* $237,244 ($47,449/year/site) ($4,745/event)	$2,649,288 ($53,185/year/site) ($5,299/event)	$112,196 ($22,439/year/site) ($2,244/event)

As illustrated in Figure 21, a regional support center does not actually reduce total costs to the Army using the given costs. This is due to the travel costs required for technicians to travel to the site. The cost of $1500/event (based on airfare, hotel, and per diem for the week) outweighs any benefit the regional support center gives from a reduction in equipment and labor needed per installation. If these travel costs are lower (e.g., due to proximity to installation), the slope of the Regional Support Center line in Figure 21 is reduced and it can become less expensive for a regional support center to perform the studies. This cost analysis is limited by the data collected through this demonstration. Since this demonstration estimated only a cost requirement to perform the VDMTS process, the relationship between cost and number of events (or installations) is a linear function. This assumption is accurate in the case of Scenario 1 and 2. As more installations adopt the VDMTS method under these scenarios, the total cost to the military increases linearly as the efforts are replicated for each installation. In the case of Scenario 3, as the number of events tracked increased, the cost per event would decrease due to economies of scale (increased efficiency of labor, decreased analyses times, etc.). However, the cost data collected in this demonstration do not allow for the determination of the decreasing costs per event collected for Scenario 3.

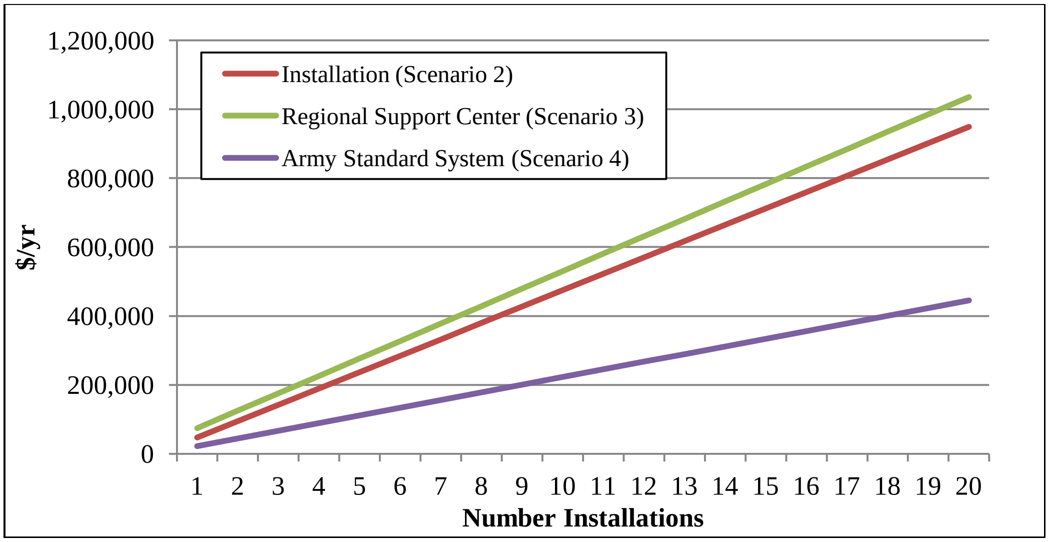

Figure 21. Total cost to Army from different scenarios with increasing number of installations adopting process.

(Assumes 10 events of 20 vehicles/event at each installation over 5 years at the costs given in Table 25)

8.3.2 Alternative Monitoring Methods and Costs

Alternative options to the VDMTS system were also identified through discussion with military land managers. However, the VDMTS process provides land managers with data and products that cannot be produced with either of these monitoring methods. This cost comparison can give an idea of VDMTS implementation costs compared with existing monitoring costs. Fort Riley is currently implementing a land change detection model based on bimonthly 250 m resolution Moderate Resolution Imaging Spectroradiometer (MODIS) data at an estimated operating cost of $2418.13 per year. However, this product was recently developed and is currently available only at Fort Riley. As such, accurate cost data for implementation at other installations are not available for comparison to the VDMTS process. The second alternative option is the "windshield survey," which is used to determine locations of highly impacted training areas and to locate LRAM sites. Fort Riley currently employs this method at an estimated cost of $47,449/year/installation. While VDMTS implementation does not completely eliminate the need for field validation of these sites, tracking a number of events per year could reduce this cost and free technician time to repair more of these impacted sites. Another added benefit which is not quantified in this analysis is the ability to use the VDMTS data for NEPA and ATTACC reporting and assessments.

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9.0 IMPLEMENTATION ISSUES

9.1 VDMTS ACCEPTANCE, ISSUES, AND ALTERNATIVES

Once individuals used the VDMTS units and utilized the data they collected, they were often impressed and excited to implement them into their programs. Initially, the technicians were generally hesitant to commit too much of their time to using the systems. After using the systems once, they were often surprised by the lack of time and effort required to collect the data. At Fort Riley and PTA, the use of the VDMTS system was implemented into the installation proposed ITAM 5-year plans. Staff at a third installation requested a proposal to track additional training events after the ESTCP demonstration project to support an existing research program on base. However despite the installation acceptance of the process, turnover at ITAM and Environmental installation branches may result in VDMTS system implementation issues. Additionally, there seems to be little continuity in programs as this turnover occurs. An original installation staff member may find the VDMTS collected data and analysis invaluable towards their program; however, their replacement may not have the time or desire to learn how the system could support their work.

Currently, the VDM tracking units are custom built by Cybernet. A lower cost alternative (Vehicle Tracking System [VTS] unit) without the INS tracking capability can be built using standard commercial off-the-shelf (COTS) components. User manuals for the VDM units are supplied in Appendix C of the Final Report. The factors involved with implementing either system or hiring a regional support center to collect tracking data are summarized in the Cost Model section (Section 8.1). The main driver for these decisions is the availability of in-house labor and capability to perform simple analysis of the vehicle tracking data.

An additional option for implementation involves using existing military standard systems (Army's BFT and National Guard's DFIRST), which obtain vehicle location and time data on live training events for post-event analysis. While this option reduces the labor required for the collection of vehicle positional information, it presents a whole new set of implementation issues. The primary issue involves getting permission to use these data. Some of these data are classified and would need to be declassified prior to obtaining them. Secondly, the quality of the data (positional and temporal) may not match those validated under this demonstration plan. A study is currently being performed to investigate data quality from these systems compared with the data collected from the VDM and VTS systems.

9.2 TECHNOLOGY TRANSFER AND IMPLEMENTATION

The demonstration plans outlined multiple methods of tech transfer and implementation to improve military land management decision making. However, as mentioned in the previous sections, our installation hosts often found value to the data collected through this work in ways we had not anticipated. The following section describes some of the different ways the data collected through this project have been used outside the scope of this project.

Fort Benning found value in characterization of vehicle travel and training area use. Discussion with installation staff led to the concept of analyzing vehicle tracking data to determine distances to RCW habitat. Previous work determined flushing responses to military training at different

distances. These data allowed Fort Benning to begin to estimate how much a certain training event could affect populations. Monitoring the vehicles with VDM tracking units was instrumental in gaining the approval of the USFWS to allow increased vehicular traffic around RCW clusters that were due to changes to the Program of Instruction (POI) for the ARC. Coordination with Fort Benning is ongoing to augment an existing research project aimed at investigating heavy maneuver effects on RCWs. These data help quantify and characterize the extent of vehicular training in RCW habitat.

Through this project we were able to support an Armor School Command sponsored Good Hope Soil Disturbance Demo project at Fort Benning. This demonstration informed command on expected soil disturbance from training events in the newly constructed training areas. We were able to support this study by supplying quantitative data on impacts and vehicle maneuvers.

Coordination is ongoing with ESTCP project RC-200820 to ensure that the data we collected at Fort Riley and PTA can be used as an input to the Kinematic Wave Rapid Soil Erosion Assessment Model. Vehicle tracking data (vegetation removal and RD) collected at PTA have been used in the model to improve estimation of vegetation cover maps (bare versus vegetation). These data can also improve the Digital Elevation Model (DEM) data as a vehicle rut can concentrate overland flow and increase the probability for gully formation.

Data collected from this project are currently informing the model development for an ERDC 6.2 study Optimal Allocation of Land for Training and Non-Training Uses (OPAL). The objective of the OPAL work package is to predict impacts for cumulative military land use activities and provide optimization routines for military land managers. This informs land management decisions and allows for estimation of past, present, and future impacts given historical and planned land use. All the separate training events we tracked through this study are being combined into a single database. Impacts and training distribution will be characterized be mission type allowing more accurate predictions of impacts from planned training events.

The theoretical models are also being adapted and modified for improvement of vehicle mobility and power requirement models. A U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) funded project, Advanced Vehicle/Terrain Interaction Modeling to Support Power and Energy Analysis, has incorporated the DW models as well as the soils database generated through this demonstration's field studies.

As described in this section, this project was successful in going outside the initial project scope by providing interested parties data and summaries for improved understanding of mission impacts to soil and vegetation. This is partially due to the variety of backgrounds of personnel who were involved with this project. Data and summaries from this project were used to brief the Headquarters, Department of the Army (HQDA) ITAM program manager, USFWS regulators at Fort Benning, and training commands. People from varying backgrounds understood how the data collected could be used to inform their land use and training decisions and model development. Implementation of this technology requires consideration of the information desired and the different options for data collection. Decisions to implement the VDMTS process must take into account the question being asked and resources available to the installation.

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